Journal of
THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

President of the Society

Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., President of the Society for the year 1955-1956, took office at the Annual General Meeting of the Society held on 5th May 1955.

Council for 1955/56

The following are the newly elected Members of Council as a result of the Ballot declared at the Annual General Meeting:

Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S.
*G. R. Edwards, C.B.E., B.Sc.(Eng.), F.R.Ae.S.
H. H. Gardner, B.Sc., F.R.Ae.S.
Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S.
B. P. Laight, M.Sc., A.M.I.Mech.E., A.F.R.Ae.S.
E. J. Mann, F.R.S.A., A.I.Mech.E., A.R.Ae.S.
*B. S. Shenstone, M.A.Sc., A.F.C.A.I., A.F.I.A.S., F.R.Ae.S.

* Re-elected.

Annual General Meeting

The Annual General Meeting of the Society was held at 4 Hamilton Place, W.1, on 5th May 1955, at which the Annual Report and Balance Sheets of the Royal Aeronautical Society and Aeronautical Trusts Limited for 1954 were approved. The Complete Report and Balance Sheets were published in the April 1955 Journal.

The retiring President, Sir Sydney Camm, presented certain of the Society's Awards to the recipients (a full list is published with these Notices).

At the conclusion of the Meeting, Mr. N. E. Rowe was presented with a Silver Salver by Mr. E. J. Mann on behalf of all the Branches of the Society, in appreciation of Mr. Rowe's work and encouragement for the Branches during his term as Chairman of the Branches Committee.

New Fellows

The following elections to Fellowship were announced at the Annual General Meeting on 5th May 1955:

Dr. J. H. Argyris
Dr. K. G. Bergin
G. B. Bolt
Air Marshal Sir John Boothman
Dr. N. A. de Bruyne
H. W. Clarke
E. J. Earnshaw
W. M. Evans
J. C. Floyd
Sir Wilmot Hudson Fysh
E. A. Gibson
Dr. G. S. Hislop
D. James
J. C. Kelly-Rogers
P. McCormack
Sir Arthur de T. Nevill
Dr. J. H. Preston
T. Simpson
Sir Lawrence J. Wackett
J. L. Watkins
F. L. Wattendorf
D. H. Williams

Graduates' and Students' Section

A visit has been arranged to the National Gas Turbine Establishment, Pyestock, Farnborough, for Wednesday 20th July 1955. The numbers for this visit are limited, and application should be made immediately to the Hon. Visits Secretary, Mr. P. D. Stewart, 217 High Road, E. Finchley, London, N.2. Applicants are asked to state their grade of membership of the Society, and that they are of British nationality.

Honorary Fellows

Honorary Fellowship of the Society has been conferred on

Dr. Igor I. Sikorsky, Hon.F.I.A.S.
Mr. H. Grinsted, C.B.E.

The Scrolls of Honorary Fellowship were presented at the Annual General Meeting on 5th May.

Medals and Prizes of the Society

The following Medals and Prizes awarded by the Society were presented at the 43rd Wilbur Wright Memorial Lecture on 19th May 1955:—

The Society's Gold Medal, the highest honour which the Society can confer for work of an outstanding nature in Aeronautics, to:

Lord Hives (*Honorary Fellow*), for his outstanding work in the field of Propulsion of Aircraft.

The Society's Silver Medal, for work of an outstanding nature in Aeronautics, to:

Dr. R. A. Frazer (*Fellow*), for his outstanding work in Aerodynamics over a period of many years; and

Dr. A. A. Griffith, for his outstanding research contributions on Aircraft Engine Design.

The Society's Bronze Medal, for work leading to an advance in Aeronautics, to:

Professor M. J. Lighthill, for his contributions to Aeronautical Knowledge.

The British Gold Medal, for outstanding practical achievement leading to advancement in Aeronautics, to:

Mr. G. H. Dowty (*Fellow*), for his outstanding practical achievement in the design and development of Aircraft Accessory Systems.

The British Silver Medal, for practical achievement leading to advancement in Aeronautics, to:

Dr. S. G. Hooker (*Fellow*), for his practical achievement in the Design and Development of Aero Engines.

The Wakefield Gold Medal, awarded to the Designer or Inventor of any apparatus tending towards safety in Flying, to:

Mr. J. Taylor (*Associate Fellow*), for the design and development of the Counting Accelerometer.

The George Taylor (of Australia) Gold Medal, awarded for the most valuable contribution read before or published by the Society on Aircraft Design, Manufacture or Operation, to:

Mr. R. C. Morgan (*Fellow*), for his paper on "Practical Experience of Airline Engineering" (September 1954 Journal).

The Simms Gold Medal, awarded for the most valuable contribution read before, or published by, the Society on any subject allied to Aeronautics, to:

Dr. D. Williams (*Fellow*), for his paper on "Recent Developments in the Structural Approach to Aeroelastic Problems" (June 1954 Journal).

The following Prizes and Awards were presented at the Annual General Meeting, held at the offices of the Society on 5th May 1955:—

R. P. Alston Memorial Prize, awarded for practical achievement associated with the Flight Testing of Aircraft, to:

MR. G. A. V. TYSON (*Associate Fellow*), for his contributions to the Flight Testing of Marine Aircraft.

The Edward Busk Memorial Prize, awarded for the most valuable contribution read before, or published by, the Society on Applied Aerodynamics, to:

MR. J. C. WIMPENNY (*Associate Fellow*), for his paper on "Stability and Control in Aircraft Design" (May 1954 Journal).

The Herbert Akroyd Stuart Memorial Prize, awarded for the most valuable contribution read before, or published by, the Society on Applied Thermodynamics, to:

MR. E. E. CHATTERTON (*Fellow*), for his paper on "Compound Diesel Engines for Aircraft" (September 1954 Journal).

The Usborne Memorial Prize, awarded for the best contribution to the Society's Publications written by a Graduate or Student on some subject of a Technical Nature in connection with Aeronautics, to:

MR. L. F. CRABTREE (*Graduate*), for his paper on "The Compressible Laminar Boundary Layer on a Yawed Infinite Wing" (Volume V, Part 2, *The Aeronautical Quarterly*, July 1954).

The Orville Wright Prize, awarded for the best contribution received for publication in *The Aeronautical Quarterly* of the Society on some subject of a Technical Nature, in connection with Aeronautics, to:

MESSRS. D. B. SPALDING and B. S. TALL, for their paper on "Flame Stabilisation in High Velocity Gas Streams and the Effect of Heat Losses at Low Pressures" (Volume V, Part 3, *The Aeronautical Quarterly*, September 1954).

The J. E. Hodgson Prize, awarded for the best paper of a general nature with emphasis on Historical Work, published by the Society, jointly to:

MAJOR G. P. BULMAN (*Fellow*), for the First Barnwell Memorial Lecture (June 1954 Journal); and

MR. J. SMITH (*Fellow*), for the First Mitchell Memorial Lecture (May 1954 Journal).

The Branch Prize, awarded for the best paper on an Aeronautical subject read before the Branches and published by the Society, to:

MR. E. CHAMBERS for his paper on "Meteorological Services for the Comet" (March 1954 Journal).

The Royal Aeronautical Society Navigation Prize, awarded for the best paper on Navigation, including Meteorological Instruments and Test Equipment, published by the Society, to:

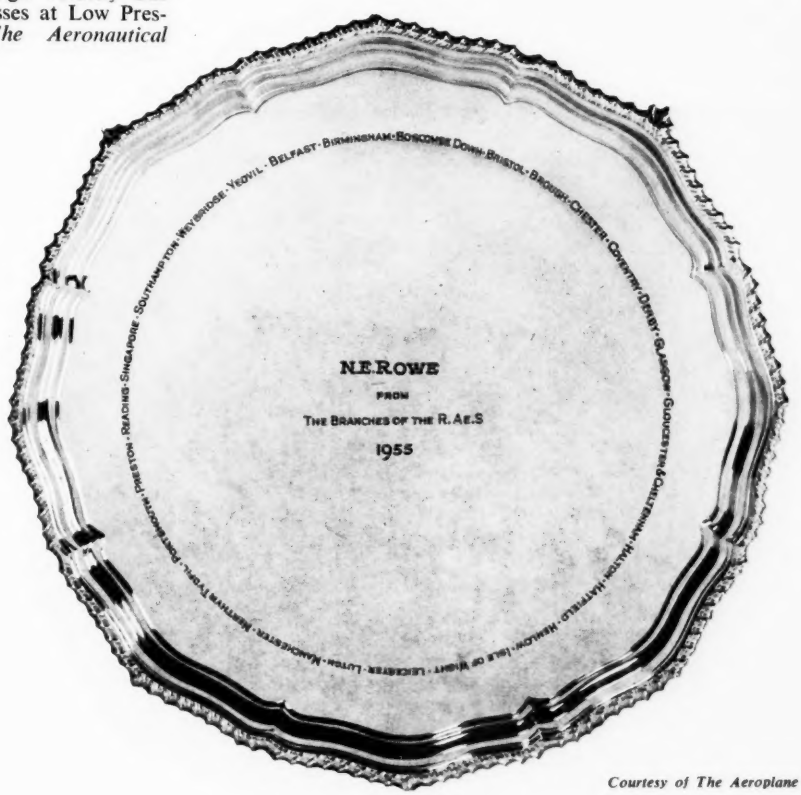
MR. J. F. W. MERCER, for his paper on "A Quantitative Study of Instrument Approach" (February 1954 Journal).

The R.38 Memorial Fund: Two awards from the Fund were made to:

LORD VENTRY (*Companion*), to assist him in the carrying out of experiments and to help in the development of the Airship *Bournemouth;* and

MR. W. N. ALCOCK (*Companion*), to assist him in his further investigations in connection with Airships.

No award has been made this year for *The Pilcher Memorial Prize*.


N.E.ROWE
FROM
THE BRANCHES OF THE R.AE.S
1955
YEOVIL · BELFAST · BIRMINGHAM · BOSCOMBE DOWN · BRISTOL · BROUGH · CHESTER · COVENTRY · DERBY · GLASGOW · GLOUCESTER & CHELTENHAM · HATTON · HATFIELD · HENDON · ISLE OF WIGHT · LEICESTER · LUTON · MANCHESTER · MARTHAM · PORTSMOUTH · PRESTON · READING · SINGAPORE · SOUTHAMPTON · WEYBRIDGE ·

The Silver Salver which was presented to Mr. N. E. Rowe on behalf of the Branches of the Society at the Annual General Meeting on 5th May 1955.

Courtesy of The Aeroplane

The Royal Aeronautical Society Prizes in Aeronautics: The following awards have been made for 1954:

Imperial College of Science and Technology: R. W. Penny and A. J. Taylor-Russell.

Queen Mary College: E. B. Davies.

University of Bristol: R. L. Dommett.

University of Southampton: M. A. Hollingsworth.

University of Glasgow: Ian A. M. Hall.

News of Members

J. W. Adderley (*Associate Fellow*) has been appointed Sales Manager of the Aircraft Division of English Electric Co. Ltd.

Group Captain B. H. Becker (*Associate Fellow*) has retired from the Royal Air Force and has been appointed Technical Manager of the Turbo-Propeller Division of D. Napier & Son Ltd.

Lord Brabazon (*Honorary Fellow*) has been re-elected President of the Royal Institution and The Royal Aero Club for a further term of office.

R. A. Clark (*Associate*) has left the Edgar Percival Aircraft Co. and has taken up a post with Aero Explorations, K.G. at Frankfurt.

W. F. Fowle (*Associate*) has left the Royal Air Force and has taken up a post with Folland Aircraft Ltd. as Apprentices Workshop Instructor.

A. B. Haines (*Associate Fellow*), formerly of Aero and Naval Air Departments, Royal Aircraft Establishment, Farnborough, has joined the Aircraft Research Association Ltd., Bedford, as Chief Aerodynamicist.

Sir Frederick Handley Page (*Honorary Fellow*) has been made an Honorary Associate of the College of Technology, Birmingham, for his services to the Aircraft Industry and to technical education.

Dr. J. H. Preston (*Fellow*) has been appointed to the Chair in Fluid Mechanics at Liverpool University (from 1st July). His previous post was Lecturer in Aeronautics of the Engineering Department, Cambridge University.

Society of British Aircraft Constructors' Educational Grants

The attention of members and others is drawn to the Society of British Aircraft Constructors' Educational Grants administered by the Society.

The Grants are designed for the assistance of young men who are unable, for financial reasons, to obtain training in aeronautical engineering. All holders of S.B.A.C. Grants are expected to qualify for a technical grade in the Royal Aeronautical Society.

Applicants should be between the ages of 16 and 18 on 1st September of the year of the award. The closing date for applications this year is 30th June 1955. Application forms may be obtained from the Secretary.

Diary

13th **June**

Halton.—Modern Aircraft Electrics. Branch Hut, R.A.F., Halton. 6.45 p.m.

20th June

Halton.—Films. Branch Hut, R.A.F., Halton. 6.45 p.m.

27th June

Halton.—Junior Members' Night. Discussion on Problems of High Speed Flight. Branch Hut, R.A.F., Halton. 6.45 p.m.

4th **July**

Halton.—The Medical Aspects of Aircraft Engineering. Wing Cdr. Latham. Branch Hut, R.A.F., Halton. 6.45 p.m.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

William Norman Bainbridge (*from Graduate*)
John Albert Barker
Maurice Sidney Binning (*from Graduate*)
Charles Barton Bovill (*from Associate*)
John George Henderson Brown (*from Associate*)
Harry Charles Channon (*from Graduate*)
John Cyril Chaplin (*from Graduate*)
George Frederick Donno (*from Graduate*)
Andrew James Duxbury (*from Graduate*)
Richard Wilfred Goddard (*from Graduate*)
Wilfred Edward Hampton
Arthur George Hancocke (*from Associate*)
John Trewyn Hawken (*from Graduate*)
Lionel Charles Heal
Ronald Clifford Hockey (*from Associate*)
Francis Pennington Lanham (*from Associate*)
Frank Madden (*from Graduate*)
George Eric Martin (*from Graduate*)
Eric Owen
James Richard Palmer (*from Graduate*)
Alfred John Penn
Albert Rickards (*from Associate*)
John Vanston Roberts (*from Associate*)
John Philip Smith
Ian Thompson Smyth (*from Student*)
Charles Frederick Cole Sneesby
John Thompson (*from Graduate*)
Geoffrey Thomas Tollett (*from Graduate*)
Jerzy Maciej Tusiewicz (*from Graduate*)
Arthur Adrian John Willitt (*from Graduate*)

Associates

Peter Philip Benstead (*from Student*)
Herbert Hay Brown
Donald Ross Downing
Cecil Stanley Knight
James Frederick Vernon Magner
Roderic Timothy Pearse O'Shea (*from Student*)

Graduates

John Anthony Albertini
Jal Merwanji Antia
Ronald Ashford (*from Student*)
Robert Edward Catterwell (*from Student*)
Tom Frisby Goodwin
Peter David Hall (*from Student*)
Thomas Henry Hallstaff (*from Student*)
Geoffrey Stanley Holister
Keith Ian McKenzie
Alan Rutherford McLean (*from Student*)
Donald Lionel Martin
Royston Kenneth Penny (*from Student*)
John Alexander Ritchie
Thomas Robertson
Edward John Scanes (*from Student*)
Ian Gourlay Strang
Kenneth Anthony Strange
Roy Thornhill
Jack Walters (*from Student*)
James Walton (*from Student*)
Edward Peter Lloyd Windsor (*from Student*)

Students

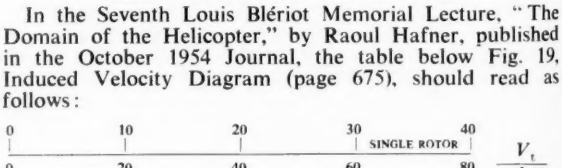
John Pearsall Hellings
Michael William Hermon
Roy Cyril Johnson
John Peter Little
Barry Benjamin Myers
Philip Hubert Osborne Pearson

Companions

William Ponter Escreet
Peter George Gillham (*from Student*)
Lewis Law
George Preskey

Correction—October 1954 Journal

In the Seventh Louis Blériot Memorial Lecture, "The Domain of the Helicopter," by Raoul Hafner, published in the October 1954 Journal, the table below Fig. 19, Induced Velocity Diagram (page 675), should read as follows:



The Journal of the Royal Aeronautical Society

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VOLUME 59 JUNE 1955 NUMBER 534

FRANK BERNARD HALFORD, C.B.E., F.R.Ae.S.

7·3·94 - 16.4.55

A TRIBUTE

IN THESE hurrying days recollection of men and their deeds of yesterday are quickly blurred by our hopes and problems of to-morrow. When the oak is struck down we miss it from the landscape as we last saw it and not as the young sapling it once was. Most of the many who will mourn the passing of Frank Halford will probably think of him as "Chairman and Technical Director of the de Havilland Engine Company"; as "President" in 1951-52 of the Royal Aeronautical Society; heavily burdened with the technical responsibility of an organisation of world wide repute; as something indeed of an Institution rather than an individual as human as themselves.

For those, however, who met him years long ago and have lived ever since in intimate and abiding friendship and the common task of fostering aero-engine development, there will remain of him an imperishable memory of an ever-young man of dynamic enterprise, warm in heart, extraordinarily magnetic, gay in adventure with the *panache* of a D'Artagnan, an echo of the Robin Hood of his beloved county of Nottingham.

For this reason I have selected to accompany this tribute a photograph taken probably just before the last war, which seems to me the most fitting as a memorial of my best friend of 40 years.

After leaving Felsted School, notable for its "Engineering Side," (where he just overlapped the older R. K. Pierson of Vickers-Armstrongs) and a short period at Nottingham University, he learnt to fly at Brooklands with the Bristol Aeroplane Co., taking his Aero Club "ticket" No. 639 in less than two months (in October 1913) and became a Pilot Instructor, aged 19. But already his burning interest was in "engines," and in April 1914 he joined the recently created A.I.D. at Farnborough, formed under the Director General of Military Aeronautics of the War Office with Lt.-Col. J. D. B. Fulton as Chief Inspector of Aircraft, and Captain R. K. Bagnall Wild, R.E. (Retd.) as Inspector of Engines—to safeguard the quality of manufacture of equipment for the Royal Flying Corps.

Halford joined as an Engine Examiner, at 50/- per 48-hour week (with 6/- per day subsistence allowance!). On the outbreak of war in August he enlisted in the R.F.C. as "Foreman Artificer" and went to France, but was commissioned as Second Lieutenant in January 1915 and re-appointed to the A.I.D. as Assistant Inspector Engines.

In those days the bulk of the aircraft and engines produced for the R.F.C. were designed by the Royal Aircraft Factory, now R.A.E., but there were contracts for French rotary Gnomes, Clergets, and Le Rhones, and the Austro-Daimler 6 cylinder water-cooled engine built under licence by Sir W. Beardmore & Co. Ltd. at the Arrol Johnston works at Dumfries. For these "foreign" "non-R.A.F." types the A.I.D. perforce (but with enthusiasm) acted as overseers of design and development and not only as inspectors, until an embryo Technical Department was set up at the War Office in 1916.

Inevitably and irresistibly young Halford leapt to the opportunity of creation of "more power," and finding a sympathy in the bluff sound T. C. Pullinger, head of Arrol Johnstons, quickly beat up the 120 h.p. Beardmore to give a reliable 160 h.p. output (a 33 per cent advance!) to the benefit of the R.A.F. F.E.2B pusher biplane.

Following a visit to France about mid 1915, he returned full of enthusiasm for the Hispano Suiza 8 cylinder 90° Vee water cooled engine with its novel aluminium monobloc cylinder construction, and advocated its building in England, under a licence obtainable for a trivial fee. But who was an impetuous lad of 21 to discuss such matters of high War Office policy, and months elapsed and a high price had to be paid before the Wolseley Co. started to produce the Hispano Vipers for the S.E.5 fighter of R.A.F. design.

Meanwhile, undeterred by this rejection of his foresight and appeal, he enlisted the support of Sir W. Beardmore and Pullinger, and almost surreptitiously designed and had built the prototype "B.H.P." 6 cylinder 200 h.p. engine, with aluminium monobloc, and somehow insinuated it in 1916 into the de Havilland D.H. 4 prototype for which the 160 h.p. Beardmore had been officially specified! That aeroplane was a notable advance, and although in the D.H. 4 production form the Rolls-Royce Eagle was fitted, a large number of D.H. 9's were built with the B.H.P. which, for production in large quantity, was taken over and modified by the Armstrong Siddeley Company to be known as the Siddeley Puma.

Early in 1916 Halford met Ricardo (now Sir Harry), then performing magic with single cylinder engines in a shed at the bottom of the garden of his house at Walton, and became an ardent disciple of that Sir Isaac Newton of the natural laws of Thermodynamics, clarifying and enunciating in simple terms fundamental principles in place of the mysteries and almost mumbo jumbo superstition, of detonation, pre-ignition, thermal efficiencies, and supercharging.

One result was the design of the R.H.A. (Ricardo-Halford-Armstrong Whitworth Elswick) 12 cylinder engine with crank case supercharging in 1917. The end of the war came before there was time to comb out the teething troubles, but the association between Ricardo and Halford continued happily, and for some two years Halford was in America dealing with the former's sleeve valve patents, and acquiring much valuable experience.

There was a post-war slump in aviation, and when he came back from the U.S.A. Halford occupied himself with the practical development of the Ricardo-Triumph motor cycle, by securing Auto Cycle Union Class records at Brooklands in August 1921 for 10 miles, and the flying 5 miles, at speeds of 76 m.p.h., and also making a good show in the not unhazardous Isle of Man T.T. race.

In 1923 he set up in private practice as a designer in a little office in North Kensington, with John Brodie (of B.H.P. days at Arrol Johnston and now a Director of the de Havilland Engine Company) as assistant, and designed and got built his 1½ litre Halford Special car which in 1924 in its first race, the J.C.C 200 miles at Brooklands, he drove into 5th place at 108 m.p.h., and gave a hard battle to the Delage, the winner in 1926, until put out by a back axle failure.

In 1924 he had shifted his office to the A.D.C. Company at Croydon who were faced with the task of disposing of large quantities of redundant war material—including hundreds of new 80 h.p. 8 cylinder Renault aero engines. From this engine Halford produced the 4 cylinder Cirrus by a process of dichotomy which, allied with the genius of his old friends Geoffrey de Havilland and C. C. Walker, resulted in the D.H. Moth, the first practical private owner type of aeroplane. Dissatisfied with the sales policy which sought to keep the engine price unduly high, he again became independent and designed the Gipsy and so became identified with, though not until later directly engaged by, the de Havilland Company. The Gipsy went on, inverted in development, to sustain the first de Havilland Comet in winning the England-Australia race in 1934, a contribution marked by the Royal Aeronautical Society in presenting Halford with its Silver Medal in 1935. The Gipsy, in 6 cylinder form, still goes on, in the Devon, and in the Duke of Edinburgh's Heron.

In parallel he was wholly responsible for the design of the 16 cylinder "H" Rapier small capacity high revving air cooled double crankshaft engine, a bold conception to give minimum drag, built by D. Napier & Son, which crossed the Atlantic E. to W. in the single seater section of the Mayo Composite project; followed by the 24 cylinder Dagger on similar lines with which one R.A.F. Squadron of Herefords was fitted as a variant of the Bristol radial engined Heyford.

There were many at the time and since who deprecated the expenditure and effort applied to these "H" engines, of which relatively little production ensued, but they could hardly deny that these two types acted as violent and effective spurs to the contemporary development of more orthodox air cooled and water cooled types, and, in themselves, under Halford's drive, established many new techniques and advancement in thought helpful in many other directions.

Still questing as ever, and by now, rather uneasily, a Director of the Napier Company, though also associated with de Havillands, in 1937 he designed the Napier Sabre 2,000 h.p. water cooled sleeve valve engine, this time in "H" form, which completed its initial type test and prototype flying in the Hawker Typhoon with exceptional (and therefore ominous) freedom from trouble, and enormous promise. Unfortunately when the inevitable troubles came —almost wholly in producing the sleeves "to stay round" —they had to be tackled under conditions of war time production and in the full glare of Service publicity and political criticism. Nevertheless the Sabre in the Typhoon was a flail of the enemy in Normandy, accounted for many V1 Doodle Bugs, and was finally paid the greatest tribute possible in its adoption by another firm as the basis of the last high powered piston aero engine put into development before the jet engine swept the board.

Despite this load of anxiety in the temporary setbacks of the Sabre, Halford was one of the first to appreciate the potential of Whittle's jet development, and early in 1941 he began, as ever in his own way, to design his own jet—the Goblin of 2,000 lb. thrust at de Havillands—going boldly for a large diameter single-sided impeller and direct air intake instead of a plenum, despite the head shaking of some of the pundits. His justification is evident enough in the D. H. Vampire, the subsequent Ghost of the Venom and Comet I, and the scope and prosperity they have brought to the de Havilland Engine Company, created under his leadership in 1944.

The Royal Society of Arts recognised his clear thinking and vision in jet development by presenting him with its Silver Medal in 1946.

Since the war, under his fertile activity and direction, have come the Sprite rocket motor and the larger Spectre, his first posthumous contribution which emerged from the veil of Security a few days only after his death.

As the faithful John Brodie, who worked with him as a brother for 32 years, so aptly wrote in his touching tribute in "The Aeroplane" of 29th April:—"Surely there is no single man in all the world of aviation who has left his personal signature so clearly over such a long period!" To that I would add that no great designer has given greater inspiration, unfailing support, and prompt and generous recognition to his staff, and thus earned so richly their loyalty and united team work — in Brodie, Moult, Arscott, and Ker Wilson, to name only some, all with him over 25 years. We can look to them with confidence to carry on and complete what he was not left long enough to do.

In the accepted sense Halford had no technical or engineering training, and no academic qualifications. He was a "natural." That fact perhaps, plus his skill in cross-examination (which would have made him a brilliant barrister), and his gift for "debunking," made some elements of "officialdom" apprehensive and suspicious of him. His enthusiasm was tremendous and unquenchable. Every new project on which he embarked was going to be a world beater, and such disappointments which sometimes followed were only comparative, and left him undaunted. He had an uncanny knack of anticipating one's questions, and one's own answer to his! To be with him was a tonic.

In his earlier days he was a fine tennis player, and a strong swimmer (nearly drowned twice). Curiously he never returned to flying after he ceased instructing in 1913, except as a passenger when his work or time required, though he was an enthusiastic and excellent motor cycle and car driver, despite two serious crashes.

In later years he was an ardent supporter and Director of the Notts County Football Club, about the only relaxation he allowed himself from unremitting work.

He habitually overworked, draining himself mercilessly of energy, unheedful of the warnings of several prolonged attacks of phlebitis, during which his bedside was always cluttered with slide rules, blue prints, and reports. His devotion to duty and unconquerable courage were shown when, as President of the Royal Aeronautical Society, he presided over the Anglo-American Conference in 1951, after being told only the day before that he was suffering from a grave malady demanding a drastic operation of uncertain success the day after the Conference ended. His tenacity of will power was shown in the fact that within two years he achieved a complete cure, only to die, in full harness, as he would have wished, from coronary thrombosis.

To his wife, his mother, aged 92, from whom he inherited his zest for life and courage, and his daughter in America, must go our heartfelt sympathy. They, as some others, will find consolation that in giving him happiness and comfort in times of ease and stress they helped to pay some of the price which high achievement demands.

The tale of Frank's achievements is not yet finally told. Some of the arrows of desire shot from his bow of burning gold have yet to pass over our heads to hearten and inspire the England he loved and served so well.

For him Shelley might have sung:—

"To defy power which seems omnipotent,
Neither to change, nor falter, nor repent,
This . . . is to be
Good, great and joyous, beautiful and free.
This is above life, joy, empire and victory."

"B.B."

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Eighth Louis Blériot Lecture

Making Aeroplanes Independent of Runways

by

GEORGES HEREIL

The Eighth Louis Blériot Lecture was given in London by Monsieur Georges Hereil on 17th March 1955 at the Institution of Mechanical Engineers, Birdcage Walk, S.W.1. Sir Sydney Camm, C.B.E., F.R.Ae.S., President of the Society, presided, and welcomed especially Monsieur Jules Jarry, President of the Association Française des Ingénieurs et Techniciens de l'Aéronautique, and members of the Association who had come from France for the occasion. Introducing the Lecturer Sir Sydney said:—

"Tonight I have the honour to introduce to you Monsieur Georges Hereil, the eighth Louis Blériot lecturer. A Doctor of Law, he is honorary Legal Liquidator of the Commercial Court of the Seine district and, in 1937, he was entrusted with the interests of the Liore and Olivier Company and of the Société Aéronautique Francaise, which had just been nationalised.

"After four years of inactivity during the German occupation he was, in 1946, appointed President and General Director of the Société Nationale de Constructions Aéronautiques du Sud-Est. In April 1948 the French aircraft constructors elected him President of the Union Syndicale des Industries Aéronautiques, of which he is today Honorary President.

"He was responsible in 1949 and 1951 for organising the aviation displays at Orly and Le Bourget as well as the Aeronautical Exhibitions. With the late Peter Vos, he founded in 1950 the Association Internationale des Constructeurs de Materiel Aéronautique, and after his Presidency of this Association for two years, according to the Statutes, he has been awarded the title of President-Founder. He is a member of the Conseil Economique and is a Chevalier of the Legion of Honour.

"Almost since the early days of aviation, runway difficulties alone have focused attention on the possibilities of direct take-off, and it is interesting to note that Blériot himself patented an arrangement of airscrews, which he hoped would shorten the ground run to negligible proportions—this in the days when aeroplanes were very lightly loaded and the take-off run was very short indeed.

"But apart from the runway difficulties, designers of military aircraft—faced with the need for more volume with less frontal area and with ever-increasing tyre pressures—have often examined the possibilities of deleting the undercarriage. It is, therefore, with great interest that we shall listen to tonight's lecture, which deals with various aspects of this development and the courageous work done on the Baroudeur."

Instead of reading the paper Monsieur Hereil gave, in English, an introduction and Professor A. R. Collar, F.R.Ae.S., member of Council of the Society, gave an excellent commentary on the figures illustrating the paper and on two films. The first film dealt with the Arbalète and the second was a colour film of the Baroudeur.

Introduction

As technical progress has improved the airborne performance of aircraft, so the difficulties associated with their take-off and landing have increased.

The grass airfields which were still commonplace at the end of the Second World War have now developed into complex arrangements of concrete runways of up to three kilometres (two miles) long, taxiways, dispersal areas, and so on. The main disadvantages of these large airfields, both for military and for civil aviation, soon become obvious:—

(*i*) The enormous expenditure in either case;
for *military* aviation this expenditure has to be approved, but it is at the expense of the production of actual aircraft—like Ugolin who ate his children so that they would not be fatherless;
for *civil* aviation, the high cost of airfield construction has hampered the development of aviation in the remote areas where it would be of particular use in raising the standard of living.

(*ii*) The lack of flexibility of air forces operating from fixed bases, thus reducing their efficiency.

(*iii*) The increase in vulnerability as destructive weapons become more highly perfected.

There are two separate points to be considered in discussing the question of take-off and landing: first the area required, and second the type of surface. In the first case the determining factors are the wing loading, the lift and the accelerating and braking power available. Sir Frederick Handley Page mentioned these points a few years ago in his Blériot Lecture* (one of this series of Blériot Lectures which have contributed so successfully to Franco-British friendship and to the exchange of technical information between the two countries). In

*"Towards Slower and Safer Flying, Improved Take-off and Landing, and Cheaper Airports." *Journal of the Royal Aeronautical Society*, December 1950.

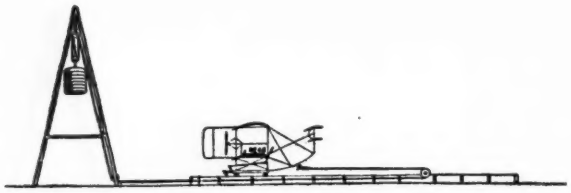


FIGURE 1. 1904. Wright Starting System. The starting rail and the derrick with dropping weight are clearly visible.

his lecture, Sir Frederick dealt particularly with aerodynamic solutions which would ensure greater safety in air transport and would reduce the cost of construction and upkeep of airfields.

In considering the second point, the type of surface, the determining factor is runway loading. The present paper is devoted exclusively to the study of problems related to this second point.

Obviously the two factors—the distance necessary for take-off and landing on the one hand and the construction of concrete runways on the other hand—are fundamentally inter-related. Eventually when an aircraft takes off and lands vertically, the runway problem will no longer exist.

Meanwhile, any new type of aircraft or, to a lesser extent, any fundamental changes in the components of orthodox aeroplanes, entails extensive project and development work which increases exponentially as higher speeds are realised. Therefore we must take note of the proverb "A bird in the hand is worth two in the bush" and, along with the long-term solutions such as Vertical Take-Off (V.T.O.) we must try to develop and perfect devices which can be rapidly applied to orthodox aircraft. It is with these devices that the present paper is concerned.

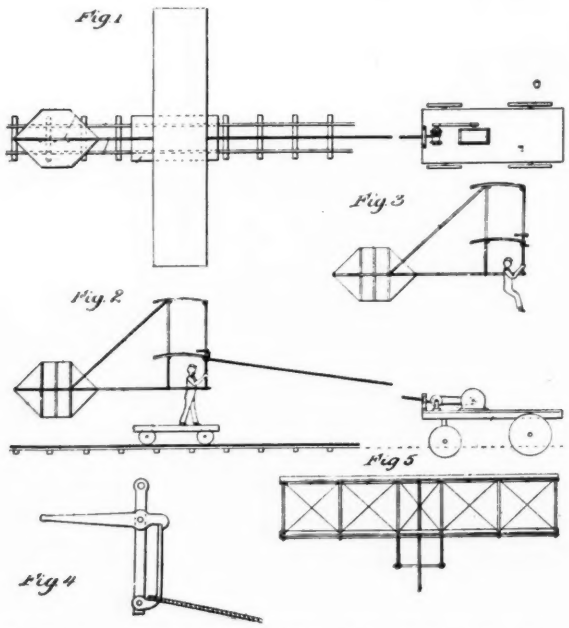


FIGURE 2. Chanute Patent, 1904. Take-off system using a trolley on rails; a line attached to the machine is wound by a power-operated winch. Note that on the drawing the operator serves as the connection between the aeroplane and the trolley.

Limiting the subject of this paper in this way will make it appear very "Down to earth," which in fact it is, and it seems desirable at this point to clarify the contents of the paper by listing all the solutions which have been considered beyond its scope.

The paper does not include V.T.O. aircraft, the forerunner of which was the German "Natter" at the end of the Second World War. During the past few years a number of projects of this kind have been developed:—

The Lockheed and Convair V.T.O. propeller-driven aircraft which differ basically from helicopters in that they change from vertical to horizontal flight by a 90° rotation of the body of the aircraft.

Vertical jet-driven aircraft such as the Ryan, the Bell and the Rolls-Royce "Flying Bedstead."

The Louis Bréguet scheme for an aircraft with rotors buried in the wing.

Annular-wing aircraft of the "Coléoptère" type, developed in France.

Jet aircraft with thrust deflection.

This paper does not consider either aerodynamic solutions or those using engine power:—high aspect ratio wings, high lift devices (including boundary layer control), rocket-assisted take-off, aerodynamic decelerating devices, by brake flaps or by parachute, engine braking, reversed thrust or decelerating rockets.

Nor does the paper consider water-based aircraft, which offer a natural solution to the runway problem and which still receive firm support both for civil and military application. There is a mention later on, however, of fighters equipped with water-skis.

Helicopters are not included either, as they are beyond the scope of the paper, as indicated by the word "Aeroplanes" in the title.

Returning to the subject to be covered, it is interesting to note that throughout the history of aeronautics inventors have conceived devices which, although not exactly solving the problems which we have today, have nevertheless embodied the essentials of the modern solutions.

For each type of solution discussed in this paper, mention is made of the most noteworthy of historical achievements of the same kind. Meanwhile it is interesting to recall briefly how the early pioneers attacked the problem.

The Clement Ader "Avion" was equipped with two small fixed wheels in front and a small cast tailwheel.

The Wright Brothers' "Flyer" (December 1903) had no wheels. Designed for use on the sandy terrain of Kitty Hawk, North Carolina, the machine was equipped with two long wooden skids which were considered ideal for landing on sand hills. For take-off the machine was supported in front by a roller on a wooden rail and, under the wings, by a wheeled trolley which remained on the ground when the machine became airborne. It was only in 1904, in their later models, that the Wright Brothers began to use their famous dropping-

weight derrick, ancestor of the launching winch and all modern cataputs (Fig. 1).

In 1904, Octave Chanute took out a patent for a take-off system for an aeroplane or a glider using a trolley running on rails and a power-operated winch winding the launching cable (Fig. 2). The great interest raised by the problem with which we are concerned is shown by the number of patents granted in the United States since Chanute's and up to March 1952. There were 158 of these, solely concerned with devices for launching aeroplanes by catapult.

We have now come to the main theme of the paper, which can be divided as follows:—

1. The limitations imposed by runways.
2. How to make aeroplanes independent of them.

PART I

The Limitations of Runways

The limitations imposed by runways have financial, economic, military and technical significance. Each of these aspects is now examined in turn.

The Cost of Modern Bases and Runways

MILITARY AVIATION

The high cost of air bases is due to the amount of labour involved and the need to use mechanical means of construction. For the release and return of operating aircraft it is necessary to choose level tracts of land several miles long and of different widths, depending on whether they are to be civil or military airfields. Surfaces of this kind are relatively rare and once the construction is completed they are irretrievably lost to cultivation. As an example some figures relating to the cost price of a N.A.T.O. airfield in France are given in what follows (Fig. 3).

Such an airfield comprises:—

(1) A runway 2,400 metres (2,600 yd.) long and 45 metres (50 yd.) wide with a border of about 60 metres (65 yd.) wide on each side and with an over-run at each end of 270 metres (300 yd.).
(2) A taxi-strip parallel to, and of the same length as, the runway.
(3) Four connecting strips.
(4) Several dispersal areas.
(5) Various access roads.

The average total cost of such a base, including lighting, radar installations, and the various airfield buildings is 2,600m. francs (£2½m.) (a breakdown of this total is given in the Appendix) of which about *half* is spent on the construction of runways. Furthermore, this base is for fighter-bombers only. For heavy bombers of the Boeing B-47 type the average cost of an airfield would be 10,700m. francs (£10½m.). It is not surprising therefore that the building of airfields places a heavy burden on the military budgets of our countries and hence reduces the amount available for actual aircraft. In the 1952 French Budget, for example, appropriations amounted to 63,600m. francs (£63·6m.) for airfields, as against only 54,400m. francs (£54·4m.) for aircraft production. This gave rise to the remark by an eminent French politician, "More millions are being buried in the ground in the form of concrete than are being spent on the construction of military aeroplanes."

CIVIL AVIATION

Civil airports are still more costly, as can be seen from the following figures:—

Idlewild—£35m. (100m. $)
Newark—£18m. (52m. $)
London Airport—£20½m.
Grand Orly expansion scheme—£30m.

FIGURE 3. A N.A.T.O. airfield.

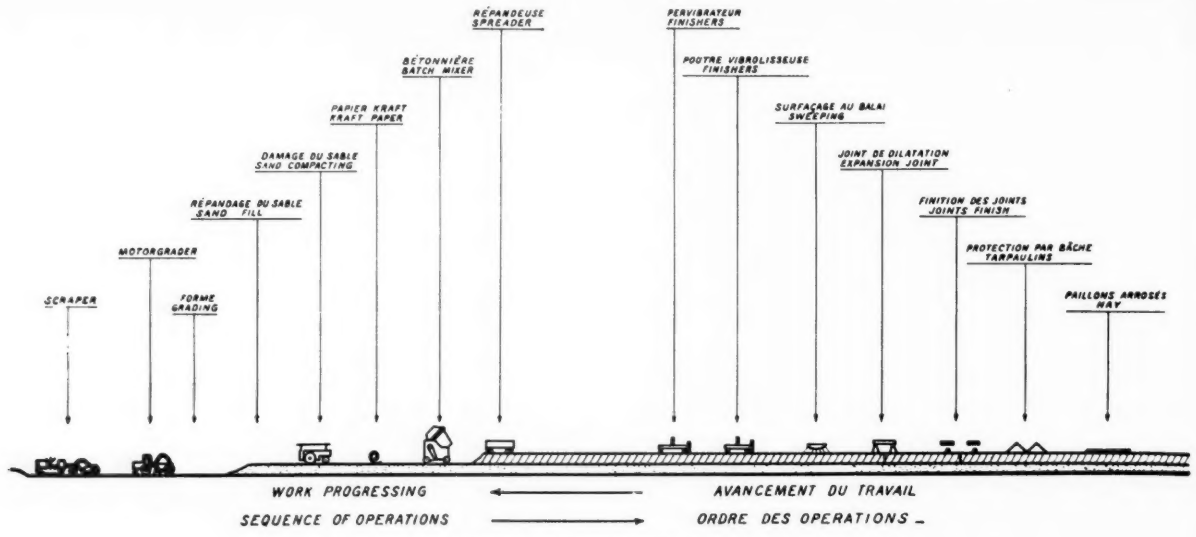


FIGURE 4. Constructing a runway.

It is true that in this case the cost of the runways is only a relatively small percentage of the total cost, on the average about 20 per cent. It must also be remembered that the structure of a civil airfield is more or less permanent, whereas military airfield construction is primarily a function of political and strategic considerations which vary even in time of peace and it also depends on the operational requirements which vary enormously in time of war.

Civil airfields are already in existence to a large extent, because the air routes most used by business and tourist traffic are more or less fixed throughout the world. Considerable sums have already been spent on the establishment of this air route network. By 1st January 1950 in the United States alone the total cost had already reached £350m., of which £230m. was for trunk route airfields alone.

It has already been pointed out that only a relatively small fraction of the cost goes on the actual runway construction. For to the runway cost must also be added, not only the cost of the ground itself and the expropriation indemnities, but also the cost of all the installations and buildings which go to make up a civil airport: these include administrative, customs, police, hotel and freight offices as well as hangars, and radar, meteorological and control services.

Each year new airfields are completed and new airports are opened to traffic. This means that the general nature of the problem of airfield construction is not the same for military and civil aviation, because, once the airports are already established, the need to find a means of eliminating runways for *civil aircraft* loses some of its importance.

On the other hand, and this point is discussed again later, it is feasible that while still using concrete runways, some of the methods designed to make military aircraft independent of them can be applied with advantage to civil air transport.

Limitations of the Use of Runways and Vulnerability

This section obviously applies to military aviation alone. In wartime, in addition to the large permanent bases, from which strategic air forces operate and which, since they are a long way from the combat zone, must be very well defended, there are a large number of "operational" airfields situated close to the front lines.

To facilitate deployment of forces, the airfield network must be well organised and it is important that this is done in peacetime. The flexibility and rapidity of interception which characterise air action are primarily dependent on the number and disposition of airfields. During the Second World War, and also in Korea, the shortage of airfields many a time paralysed air operations.

While the piston-engined aeroplane of the 1939 era sometimes allowed the Germans to improve the deployment of their forces, in particular by using sections of the autobahns, it is not possible to use the jet aircraft of today in a similar way. Thus in Korea it was the absence of a number of conveniently situated bases which demanded of the United States Air Force a veritable "tour de force," in order to use its fighters and striking forces.

Air activity was considerably reduced, in number of sorties and in duration, because the aircraft used up most of their range in flying to and from their bases. It is significant that, for the same number of aeroplanes engaged, the number of daily sorties in Korea was 260, compared with 5,000 in 1944 on the Ardennes front. The effectiveness of air striking power is reckoned by the number of sorties times the destructive load carried; this takes account of the rapidity of interception when attacking mobile targets, and is very much higher when bases are near the combat zone. Mangin said that the best place for artillery was near the front line. This applies equally to tactical aviation, the new form of

artillery. It is only safety considerations—the range of heavy artillery and the minimum time of warning of enemy attacks—which determine the distance of airfields behind the front line. Even if it were possible to construct in peacetime a sufficient number of bases near the probable combat zone, the possibility of changing battle lines has to be considered.

This leads to a discussion of the time factor involved in the construction of present day runways. Recent military history shows us two good examples of this. The first relates to the Berlin Airlift; the Tegel base, built during the most critical period by 17,000 Berlin men working in three shifts, took three months to complete. The second example is in Korea; K6 airstrip was started on 16th September 1952, and was not completed until 13th February 1953, about five months later.

This time factor was one of the causes of the downfall of the Luftwaffe in the battle of Germany. Lack of time prevented the construction, behind the Siegfried Line, of the runways necessary for the operation of Messerschmitt 262 jet fighters. The German High Command, which had a highly developed airfield network in the occupied countries on the Channel and Atlantic coasts, had not foreseen that one day it would be necessary to fight on German soil, or that their troops would have to make such a rapid retreat.

It is the number of different operations, illustrated in Fig. 4, which are responsible for the long time taken to build runways.

The important work of excavation, moving about 400,000 m.^{3} (14 million cubic feet) obviously needs powerful mechanical equipment; tractors, scrapers, bulldozers, motorgraders, and so on. For surfacing, concrete mixing plants, with an output of over 100 m.^{3} (3,500 cu. ft.) an hour, are established on the site. Although all the points discussed so far apply particularly to tactical aviation, the runway problem applies also, but in a different way, to military air transport. It is only possible to supply supporting columns, or encircled units, as numerous examples have proved, if equipment is used which is not subject to the restrictions imposed by concrete runways. "If we look for reasons for the Stalingrad defeat, the first consideration was lack of airfields," writes General Guderian, who concluded: "Reconnaissance and fighter 'planes, and especially transport 'planes, must keep in close contact with ground forces; in most cases they must be able to take off and land in the actual battle zone."

To all the disadvantages of large modern air bases must be added one more—the last but not the least. It is obvious that the long concrete runways, impossible to camouflage and very vulnerable to attack even with ordinary bombs, would be sitting targets for atomic

FIGURE 6 (*above*). A runway after a bombardment.

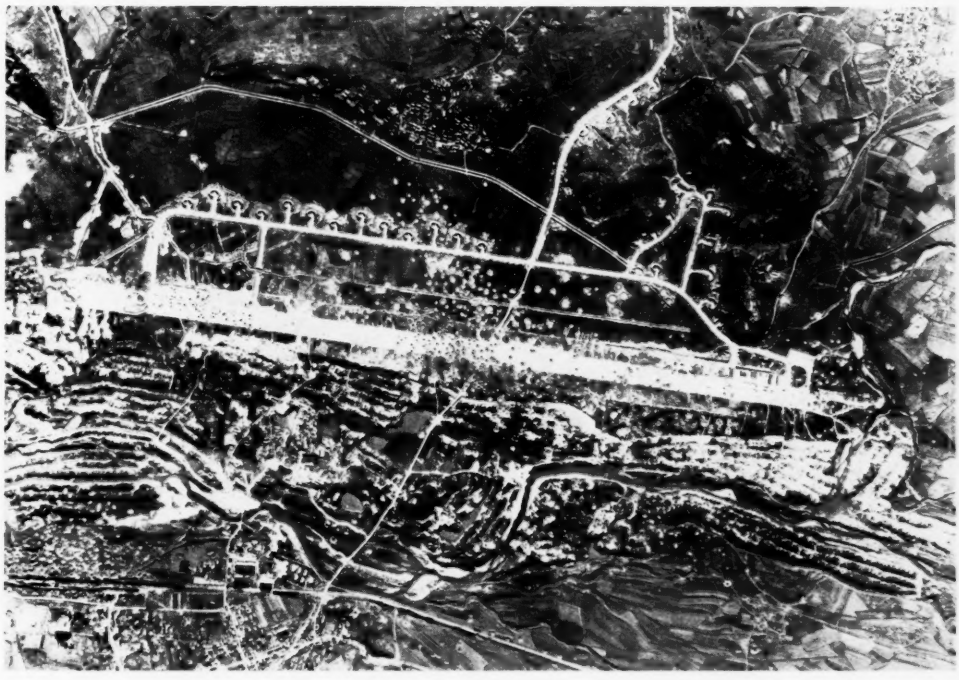


FIGURE 5 (*right*). Aerial view of a bombed runway. The craters seen beyond the runway are actually aircraft dispersal alveoles.

attacks. Figs. 5 and 6 show the results of an air attack on a runway during the Second World War. A study of the probable effects of an atomic air attack on an airfield is referred to in the Bibliography. It is shown that such an attack would be dangerous, not only because of its immense destructive effect, but also because of the contamination of equipment, installations, and even the ground itself, the effects of which could in some cases last several days. Thus it can be seen that these large airfields must cause grave concern to technicians and army and air force commands, whose efforts are directed towards the same object; never to construct objectives important enough to justify an atomic attack.

What then are the reasons for the development of our airfields over the past fifteen years? The first French runway was built in 1939 at Bordeaux, Merignac, and in other countries runways date back to about the same time. There are two points to consider; the surface of the runway and its length.

The Need for Concrete Runways

The need for concrete runways is caused by increased tyre pressures, which in turn result from increases in loading. The general trend of increasing aircraft weight has led either to an increase in tyre size or to more wheels, while at the same time the streamlining of aircraft, the reduced thickness of wings and the extra equipment, armament and fuel reserves, have all reduced the space available for wheel retraction. The most simple solution was adopted—increasing tyre pressure. This has gradually increased from the 3·6 kg./cm.^{2} (51 lb./in.^{2}) of the Dewoitine 520 and the 4 kg./cm.^{2} (57 lb./in.^{2}) of the F.51D "Mustang" to the Mystère IV's 14 kg./cm.^{2} (200 lb./in.^{2}) and the Republic F.84's 18 kg./cm.^{2} (255 lb./in.^{2}). A table showing the tyre pressures of some military and civil aircraft is given in an Appendix.

The Need for Long Runways

The need for still longer runways has been dictated partly by technical developments, and partly by safety considerations.

(*a*) *Technical Reasons*

Improvement in the airborne performance of aircraft has been brought about by two factors; reduced drag and increased power.

Drag reduction has been achieved by a high degree of streamlining and by a reduction in wing area. In spite of the general use of high lift devices, the increase in wing loading arising from the reduction in wing area has resulted in high take-off speeds. However, thanks to the large amount of excess power available at take-off with piston engines, take-off distances have not increased as much as they might have done*, but, because of the special characteristics of turbo-jets (power increasing with speed, economical cruising r.p.m., close to maximum r.p.m., poor efficiency at low speeds) the advent of jet propulsion has aggravated the penalties of high take-off speeds. The take-off distance has increased progressively from 218 m. (238 yd.) for the Dewoitine to 520 to 830 m. (910 yd.) for the Mustang and 2,150 m. (2,350 yd.) for the F.84E. A table is given in the Appendix showing the take-off distances of some civil aircraft and also the accelerate-stop distances resulting from the application of the I.C.A.O. requirements.

*Power loading has varied very little over the years in relation to take-off power.

TABLE I

I.C.A.O. RECOMMENDATIONS FOR THE CLASSIFICATION OF AERODROMES

Class	*Length of main runway*	*Tyre pressure: kg./cm.^{2} (lb./in.^{2})*
A	> 2,550 m. (2,800 yd.)	8·5 : (120)
B	2,150-2,550 m. (2,350-2,800 yd.)	7 : (100)
C	1,800-2,150 m. (1,970-2,350 yd.)	7 : (100)
D	1,500-1,800 m. (1,640-1,970 yd.)	7 : (100)
E	1,280-1,500 m. (1,400-1,640 yd.)	6 : (85)
F	1,080-1,280 m. (1,180-1,400 yd.)	5 : (71)
G	900-1,080 m. (985-1,180 yd.)	2·5 : (35)

(*b*) *I.C.A.O. Requirements*

The work of I.C.A.O. has contributed to a large extent to the lengthening of runways used by civil aircraft. This is the price of the safety represented by the new regulations as compared with the earlier I.C.A.N. regulations. A comparison of the two take-off requirements is included in the Appendix. As a result, for a machine like the Constellation, for example, whose take-off distance is 600 m. (650 yd.), the accelerate-stop distance is 1,500 m. (1,640 yd.).

Having laid down the requirements for a Certificate of Airworthiness and, of particular interest here, for take-off performance, I.C.A.O. tried to establish an operational classification for aerodromes; that is to say, a classification which would combine the characteristics of the airfield with those of the aircraft which would normally use it. This attempted classification was not completed, but it is nevertheless possible, without violating its intentions, to summarise the recommendations of Appendix 14 of I.C.A.O., as shown in Table I.

It will be noticed that for Class A aerodromes, no figure is given for the maximum length of runways. However, the figure of 2,550 m. (2,800 yd.) appears likely to cover the foreseeable future, in civil aviation, and in any case designers of new civil aircraft realise that take-off distance is an important sales factor.

PART II

Means of Making Aeroplanes Independent of Runways

The various means of making aeroplanes independent of runways are discussed in the following order (Fig. 7):—

(1) Means requiring both ground installations and a source of energy.

These include:

(*a*) Ground catapults—used for take-off only.

(*b*) The Arbalète—which is used for take-off and may with certain installations be used also for landing.

(2) Means requiring ground installations without a fixed source of energy.

These include:

(*a*) For both take-off and landing: metal tracks.

(*b*) For take-off only: Launching ramps, Trolleys running on rails, Devices for take-off on cables.

(*c*) For landing only: Ground run braking devices and belly-landing systems.

(3) Methods requiring neither ground installations nor a fixed source of energy.

These include:

(*a*) Devices which are part of the aircraft:
Low pressure tyres } for take-off and
Caterpillar tracks } landing.
Skis and Skids—for landing and, in some cases, take-off.
Combined skids and wheels—for take-off and landing.

(*b*) Devices remaining on the ground:
The combined skids and trolley system—for take-off only.

Catapults

Strictly speaking the catapult is a *launching* system. It is therefore designed in the first place to reduce the take-off distance of an aeroplane by applying to it a propulsive force from a fixed point on the ground. This force is added to the normal propulsive power of the aircraft.

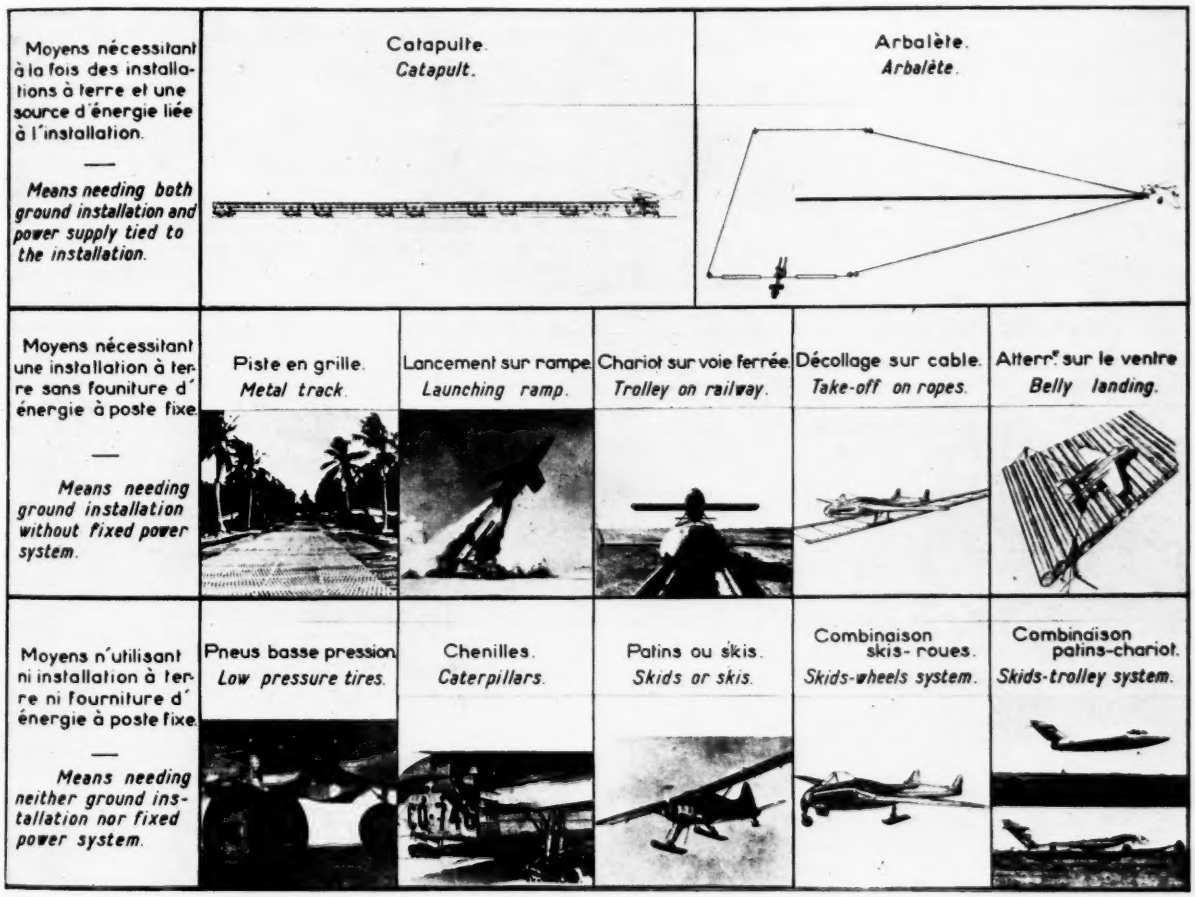

Moyens nécessitant à la fois des installations à terre et une source d'énergie liée à l'installation.
Means needing both ground installation and power supply tied to the installation.
Catapulte.
Catapult.
Arbalète.
Arbalète.
Moyens nécessitant une installation à terre sans founiture d'énergie à poste fixe.
Means needing ground installation without fixed power system.
Piste en grille.
Metal track.
Lancement sur rampe.
Launching ramp.
Chariot sur voie ferrée.
Trolley on railway.
Décollage sur cable.
Take-off on ropes.
Atterr.t sur le ventre
Belly landing.
Moyens n'utilisant ni installation à terre ni fourniture d'énergie à poste fixe.
Means needing neither ground installation nor fixed power system.
Pneus basse pression.
Low pressure tires.
Chenilles.
Caterpillars.
Patins ou skis.
Skids or skis.
Combinaison skis-roues.
Skids-wheels system.
Combinaison patins-chariot.
Skids-trolley system.

FIGURE 7. Some methods of eliminating the need for runways.

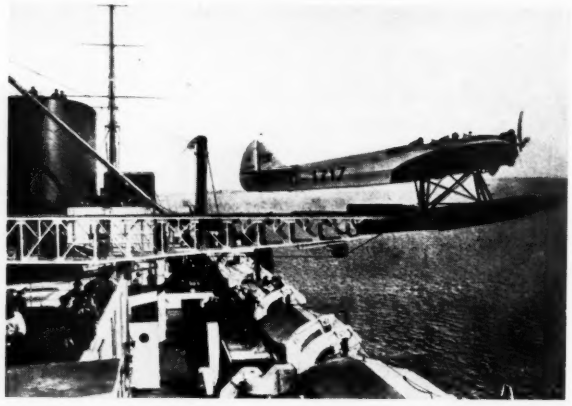


FIGURE 9. 1934. Launching of Heinkel HE-12 postal seaplane from the *Bremen*, using a Heinkel swivelling catapult.

Aircraft gross weight	...	7,700 lb.
Maximum take-off speed	...	68 m.p.h.
Launching run	... ...	65 ft.
Braking run	... ...	10 ft.
Maximum acceleration	...	3*g*.

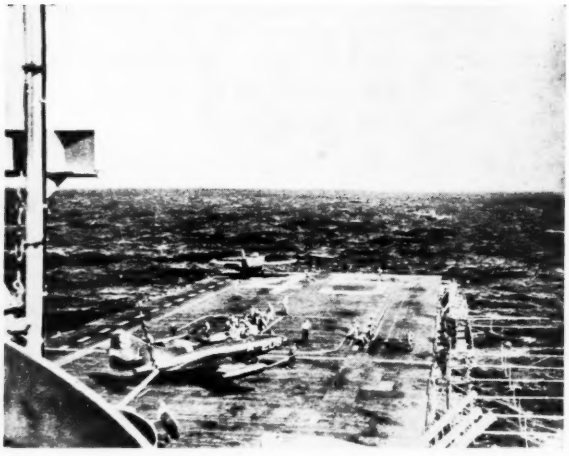


FIGURE 10. A modern carrier with two catapults.

FIGURE 11. Launching of a carrier-based fighter by steam catapult. Clearly visible are the slot of the cylinder and the cloud of steam escaping from it.

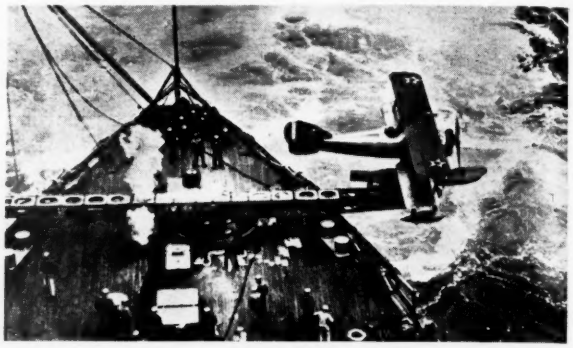


FIGURE 8. 1926. Catapulting a single float seaplane from the *Tennessee*.

The *track* which is part of most catapult installations is only a secondary item, but it is of particular interest here because it is the track which dispenses with the concrete runway.

THE WRIGHT CATAPULT

The first practical example of an aeroplane catapult was that of the Wright Brothers (Fig. 1). The added propulsive force was provided by a falling weight and the track consisted of a wooden rail with a little wheeled trolley on which the machine rested.

DECK CATAPULTS

Since this first example, catapults have been used mainly for aircraft carriers. It would take too long even to mention the various types of catapult devised—from Chambers, who in 1912 was said to have originated their use for this purpose, to the modern steam catapults with which the latest aircraft carriers are equipped (Figs. 8-11). The main point to remember is that whereas for a long time the aircraft to be launched were carried on trolleys on rails, today the machine actually runs on the flight deck. This is sufficiently strong to withstand the aircraft loading (the most recent catapults are for aircraft weighing up to 50 tons). Thus the question of tyre pressure does not apply in the same way to carrier-borne aeroplanes as it does to landplanes. Moreover, it was for this reason that the Short Seamew was equipped with an undercarriage using high pressure wheels on aircraft carriers and low pressure ones on land.

THE PROBLEM OF GROUND CATAPULTS

The ship's catapult has always tempted engineers to try to obtain the same reduction in take-off distance for land-based aeroplanes. There are two types to be considered in addition to the carrier type; a permanent installation answering the needs of an air base in regions devoid of suitable ground, and a mobile installation for use by an army in the field. The basic differences between these three types are as follows. On an aircraft carrier, take-off is assisted by the forward speed of the ship and often by a strong wind. In all, it is usually possible to count on a forward speed component of 60-90 km./h. (30-50 knots) which therefore reduces the

speed demanded of the catapult. Also, the ship's engines can provide all the power necessary for the catapult; the problem is still further simplified by the recent development of the steam catapult. Finally the weight of the installation presents no difficulties.

Obviously for ground catapults no help can be expected from the forward speed of the carrier. At best they can be erected in the direction of the prevailing wind.

Catapults in the field must, in addition, possess the essential quality of mobility. The whole installation, including the power supply, must be of a weight which can be easily transported across country. The dismantling and re-assembly must not involve excessive time and labour. Finally, the delay between the launching of one aeroplane and the next must be as short as possible.

The most important factors of the catapult are the launching length and the power required. These are determined by the following characteristics: the minimum stalling speed and control speed, and the weight of the aircraft to be launched, as well as the maximum acceleration which a normal pilot in a sitting position can endure (4-6 *g*). When the aircraft is carried on, or towed by, a trolley, the distance required for braking the trolley must be added to the launching length.

PERMANENT GROUND CATAPULTS

At present permanent ground catapults for piloted aeroplanes are not regularly used. Those devised during the past 10 years have been mainly for experimenting in the application of the different systems to various uses. The three basic characteristics of catapults are:—

1. The form of propulsion used: electricity, compressed air, steam, explosive charge.
2. The method of supporting the aircraft: sliding or rolling trolley, rail track, aeroplane running directly on the ground.
3. Type of drive used: towing cable with reeving or unrolling from a drum, direct towing by a hook, reaction force.

Before discussing more fully existing or proposed catapult schemes using these various principles, a short description is given of steam and inertia catapults. For the others, the illustrations provide the best description.

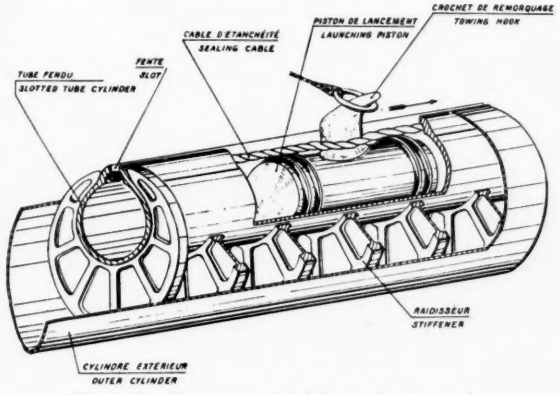


FIGURE 12. Steam catapult (schematic diagram).

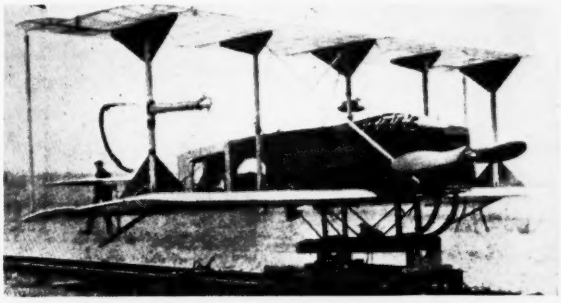


FIGURE 13. 1918. Curtiss-Sperry "Flying Bomb" pilotless aircraft, launched by a flywheel catapult. The launching trolley and the railway track may be seen.

Steam catapults use the principle of a cylinder with a slot lying along a generator. The piston in the cylinder is driven by steam pressure and a hook attached to the piston runs in the slot and pulls the aeroplane. The slot is sealed by a flexible cable which moves with the piston and is pressed against the lips of the slot by the steam pressure (Fig. 12). The cylinder has to be of the same length as the aeroplane take-off run but it avoids the complications of elaborate reeving systems. Such catapults are at present in operation, particularly in the United States at Naval Proving Grounds. The same principle was used by the Germans with the V1 catapult, but in this case the propulsive force was the reaction of liquid fuels*.

Inertia catapults use an electric motor to rotate a heavy flywheel, which stores the energy needed for launching. The aircraft is towed by a cable which unwinds from a drum driven by the flywheel. It is interesting here to recall that a flywheel catapult, developed in the United States by Norden, well known as a bomb-sight designer, was used in 1918 to launch one of the first guided weapons, the Curtiss-Sperry pilotless "Flying Bomb" (Fig. 13). On the same principle a catapult for commercial aeroplanes was planned a few years ago in France by M. Vaubourdolle, S.N.C.F. Engineer, at the request of A.F.I.T.A.

For commercial aeroplanes also, an original scheme was suggested in the United States by Lewis A. Rodert, of the N.A.C.A. The Airfract, with no landing gear, was launched from an electric rail-car and landed on a similar car, the speed of which was synchronised by radio with that of the aeroplane. Figs. 14 and 15 illustrate some of the catapults just discussed.

FIELD CATAPULTS

Junkers: At the end of the Second World War the Junkers Company designed a field catapult for launching jet fighters. The take-off weight of the aircraft was three tons and the take-off speed 75 m./sec. (145 knots). The catapult was of the inertia type and weighed 10-12

*A catapult devised on the same principle, but using a cordite charge, is believed to have been tried out last year (1954) in Great Britain.

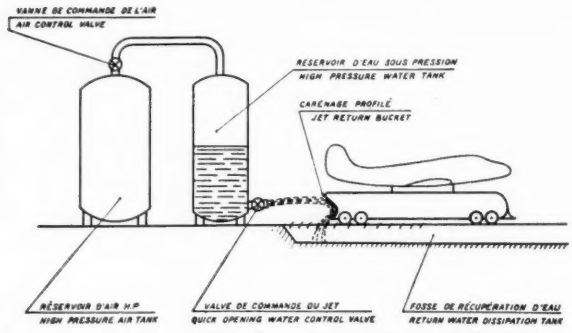


FIGURE 14. Schematic drawing of hydraulic catapult system.

tons. Two D.C.A. trailers were used to transport it. The aircraft were to take off every 30 sec. with a run of 250 m. (270 yd.). The war ended before work on the catapult was completed.

Latécoère: The Latécoère catapult is the most recent French field catapult and the author is indebted to the company and to its director, M. Moine, for providing the information given here and also to the Services Officiels Français for their permission.

The Latécoère catapult (Fig. 16) comprises a closed tube containing a piston driven by compressed air. A cable is attached to the piston and, after passing round a guide pulley, pulls a trolley. This trolley, which runs on rails, carries the aircraft to be launched. Cylindrical tubes are used as accumulators, with air compressed at 200 kg./cm.^{2} (2,845 lb./in.^{2}). The air is then released at a pressure of 30-50 kg./cm.^{2} (427-711 lb./in.^{2}) into another cylindrical reservoir forming a low pressure tank. A particularly interesting point about this machine is the system used for reheating the air. The combustion of a very small quantity of kerosine injected into the circuit results in a considerable economy of compressed air. The compressed air at 30-50 kg./cm.^{2} is passed into the cylinder and works the piston. The rails and cylinders mounted on a lattice girder framework, form a complete structure of five sections which fit together end to end (Fig. 17). The sections are mounted on trailers and are assembled by bringing the trailers one behind the other and jacking them up to the same level. To transport them by road each trailer is attached to a tractor. Three of these carry compressors driven by the tractor engine; the first section contains the trailer braking equipment and the last section the equipment for hoisting the aeroplane into position. This 60 m. (65 yd.) ramp (50 m. for launching and 10 m. for braking) is composed of sections no longer than 14 m. (46 ft.) and the width when *en route* is 3 m. 20 (10½ ft.). It can be assembled in three hours on level ground. The launching rate is expected to be five light aeroplanes in five minutes and the launching speed is 75 m./sec. (145 knots).

CONCLUSION

From an operational point of view the field catapult offers an interesting solution when it is designed, like the Latécoère, for relatively easy transportation and assembly. The cost of launching is very small, neglecting depreciation of the catapult, and in any case it is difficult to predict the total number of launchings per

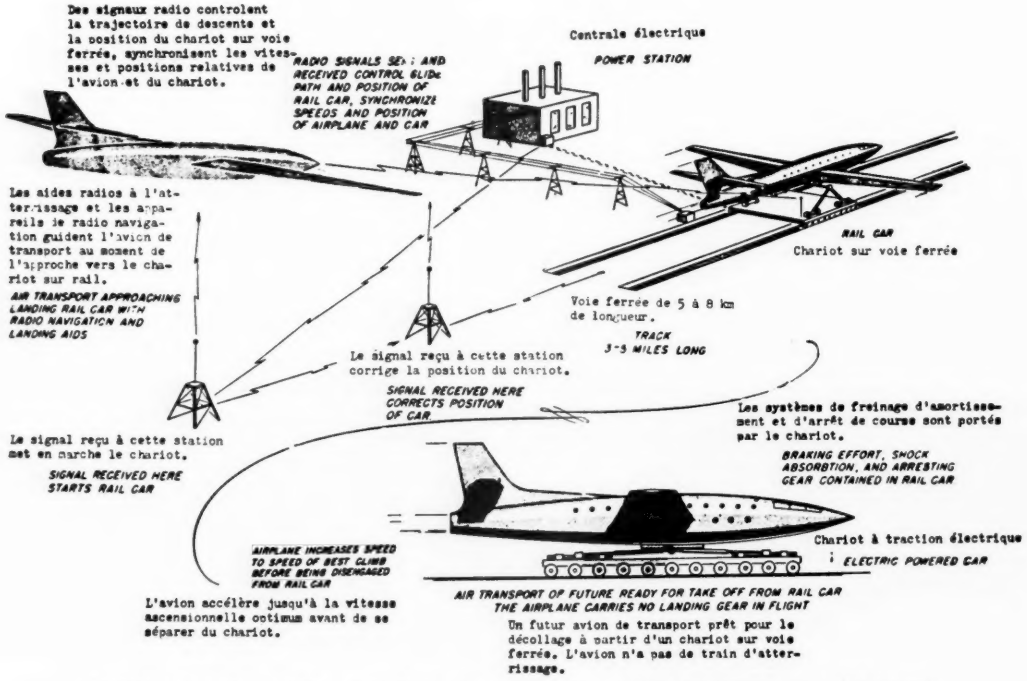

Des signeux radio controlent la trajectoire de descente et la position du chariot sur voie ferrée, synchronisent les vitesses et positions relatives de l'avion et du chariot.
RADIO SIGNALS SEND AND RECEIVED CONTROL GLIDE PATH AND POSITION OF RAIL CAR, SYNCHRONIZE SPEEDS AND POSITION OF AIRPLANE AND CAR
Centrale électrique
POWER STATION
Les aides radios à l'atterrissage et les appareils de radio navigation guident l'avion de transport au moment de l'approche vers le chariot sur rail.
AIR TRANSPORT APPROACHING LANDING RAIL CAR WITH RADIO NAVIGATION AND LANDING AIDS
RAIL CAR
Chariot sur voie ferrée
Voie ferrée de 5 à 8 km de longueur.
TRACK 3-5 MILES LONG
Le signal reçu à cette station corrige la position du chariot.
SIGNAL RECEIVED HERE CORRECTS POSITION OF CAR
Les systèmes de freinage d'amortissement et d'arrêt de course sont portés par le chariot.
BRAKING EFFORT, SHOCK ABSORBTION, AND ARRESTING GEAR CONTAINED IN RAIL CAR
Le signal reçu à cette station met en marche le chariot.
SIGNAL RECEIVED HERE STARTS RAIL CAR
Chariot à traction électrique
ELECTRIC POWERED CAR
AIRPLANE INCREASES SPEED TO SPEED OF BEST CLIMB BEFORE BEING DISENGAGED FROM RAIL CAR
L'avion accélère jusqu'à la vitesse ascensionnelle optimum avant de se séparer du chariot.
AIR TRANSPORT OF FUTURE READY FOR TAKE OFF FROM RAIL CAR
THE AIRPLANE CARRIES NO LANDING GEAR IN FLIGHT
Un futur avion de transport prêt pour le décollage à partir d'un chariot sur voie ferrée. L'avion n'a pas de train d'atterrissage.

FIGURE 15. 1946: Artist's impression of a launching and landing system for a high-speed transport aircraft. There is no landing gear and the aircraft is launched from and lands on a synchronised electric powered car. From a paper by Lewis A. Rodert (N.A.C.A.).

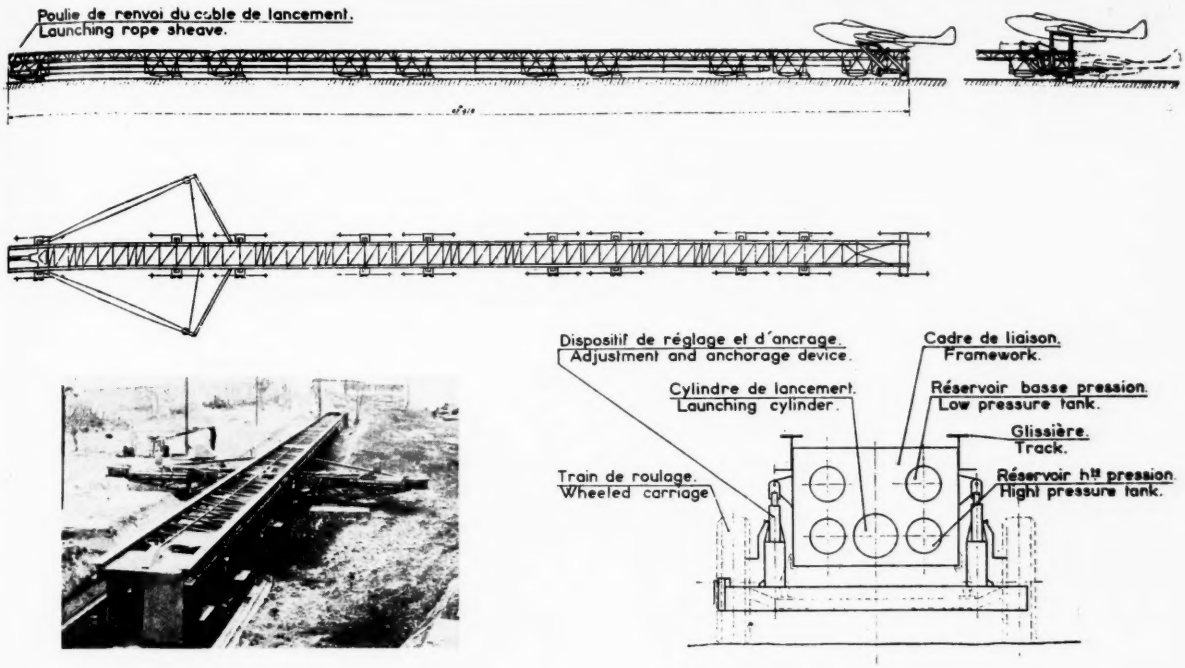


FIGURE 16. Latécoère Field Catapult. *Top*: Schematic drawing of the assembled catapult, with an aircraft at the starting point. ON THE RIGHT: Aircraft positioning. ON THE PLAN FORM can be seen the trolley braking device at the front end. *Bottom*: LEFT: Assembled catapult, three-quarter front view. RIGHT: Schematic section of the power system.

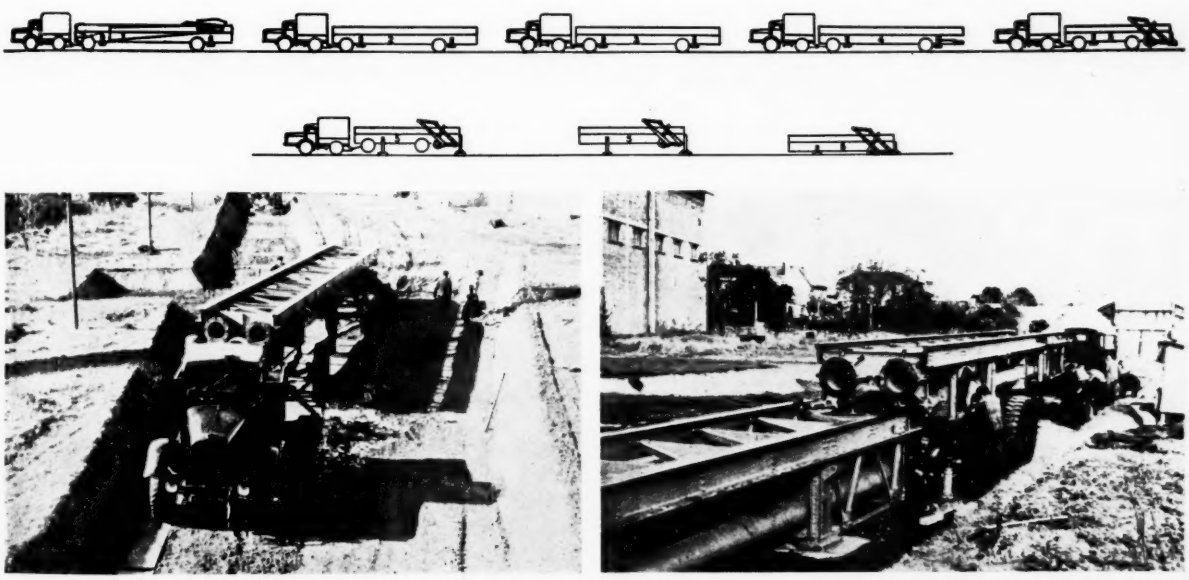


FIGURE 17. Latécoère Field Catapult. *Top*: The five trailers and their tractors making up the convoy. On the sketch below can be seen the three phases of the fifth section positioning: Uncoupling and placing on jacks; removal of the tractor; lowering to the appropriate height. *Bottom*: LEFT: Third trailer arrival and positioning. RIGHT: Second and third trailer positioning.

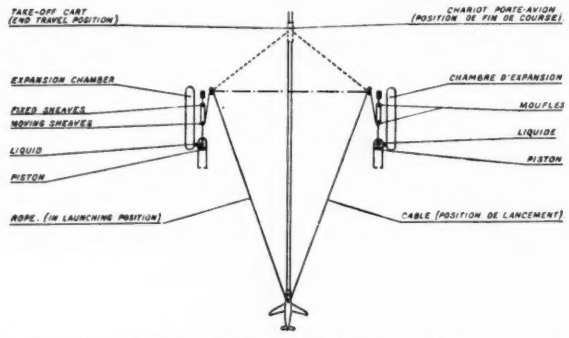


FIGURE 18. Schematic diagram of the launching system of the Arbalète.

catapult in time of war. However, the possibilities of camouflaging a 60 m. (66 yd.) ramp are excellent and so it is highly probable that the catapult would compensate for its cost by a large number of launchings. However, compared with a runway, the launching rate of a catapult is limited to some extent by the time needed for accumulator re-charging. For a high launching rate with no time wasted, several catapults would be needed for each launching station, with a corresponding increase in cost of equipment and transport.

The problem of landing still remains. The catapult can launch any type of machine, but an aeroplane with high pressure tyres landing on anything but a runway would sink into the ground, to an extent depending on the softness of the soil. Transporting and hoisting equipment would therefore be needed to extricate the aeroplane and put it back on to the catapult. A machine with low pressure tyres could land on the type of airfield existing in 1939 and the catapult could be installed on the edge of it. The size of the field could be reduced by using arrester gear similar to that used on an aircraft carrier. But, apart from the fact that low pressure tyres

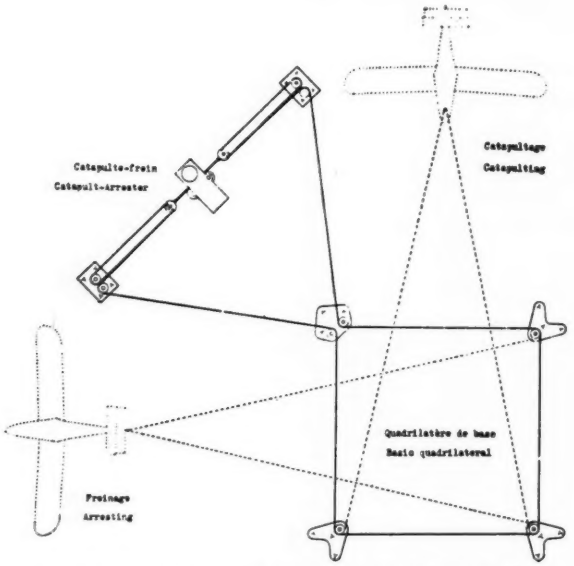


FIGURE 19. Schematic plan view of the Arbalète NC.856.

give a poorer performance, there remains the point that the movement of aeroplanes on the ground would tend to be much more noticeable to the enemy and thus the catapult would lose the relative safety given by camouflage.

If, however, the aeroplane were equipped with skids instead of wheels it could land in any confined space without the use of ground braking devices, but the disadvantages just mentioned would still exist, aggravated perhaps by the increased difficulty of hoisting the machine on to the catapult.

The Arbalète

The Arbalète is a particular type of catapult designed by M. Fieux, consulting engineer of the Société des Forges et Ateliers of Creusot (the Schneider works) to whom we are indebted for a great deal of the information which follows. The author is grateful to the Schneider Company and to the SNCA-N and its Director, M. Coroller, for their contribution to this paper.

Compared with catapults of the usual cable type the Arbalète contains some original characteristics and has therefore been treated separately. The principle is illustrated in Fig. 18 which shows:—

(*i*) A trolley, carrying or towing the aeroplane to be launched, placed on the rails.
(*ii*) A reeving system with fixed and moving sheaves.
(*iii*) A system for supplying and storing energy.

In the launching position the trolley is attached to the cables to form an acute-angled V, the cable being kept taut by pressure (compressed air, for example). The aeroplane is held near the tail by a hold-back link which is released as soon as the forward thrust reaches a predetermined value (this link is not shown in the diagram). The launching run ends when the cable becomes perpendicular to the aircraft's path, but the trolley continues under its own inertia and is then braked by the same power which is used for launching.

This is one of the interesting points about the Arbalète. The other, which is also a result of this "reversibility," lies in the possibility of using the same equipment to reduce the landing run. In this case the aeroplane is not carried on the trolley but runs on the ground and is arrested by the cable.

The Arbalète is then automatically re-loaded for a new launching and no energy has been consumed. If the time factor or other circumstances demand different arrangements for take-off and for landing, the re-loading can be done by a tractor or a winch bringing the trolley back to the starting point. In this case a small amount of energy is used up.

The first Arbalète designs date back to 1939 when the Services Techniques Français asked M. Fieux—who had a great deal of experience of deck-landing problems and whose arrester gear was almost universally used—to try to find a solution to the take-off and landing problems of landplanes. The Armistice of 1940 interrupted his work, but it was resumed a few years ago. A scheme was prepared for the launching of a light

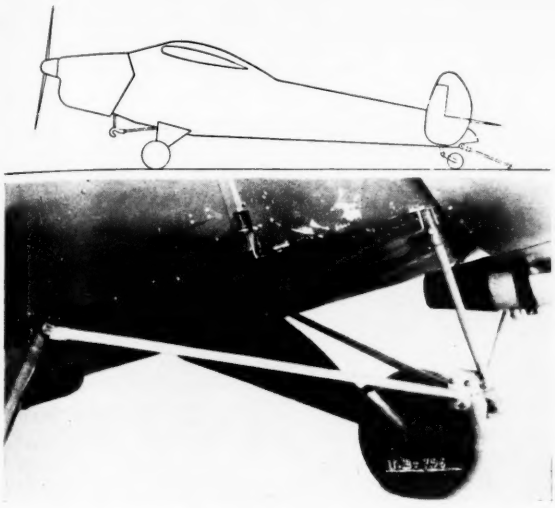


FIGURE 22. (*Above*) Sketch showing the forward towing hook and the rear arrester hook. (*Below*) Detailed view of the towing hook at the apex of a tubular bracing.

fighter of 2,500 kg. (5,500 lb.). The layout was the same as the one just discussed, but the propulsive force was provided by the expansion of gas by powder combustion. This project was never finally completed for various reasons.

However, a very interesting experiment was made with great success a few months ago in France. The principle of the Arbalète was unchanged, but was applied this time to an artillery observation aeroplane*, the NC.856, weighing about 900 kg. (2,000 lb.). The rail and trolley were no longer necessary, and the machine ran directly on the ground. The cable was passed round a system of sheaves anchored by steel stakes to form a square of side 12 m. (40 ft.). Fig. 19 shows the aircraft in take-off and in landing position; for clarity these two positions are shown at an angle of 90°, whereas in fact the positions chosen will be such as to gain the most advantage from the prevailing wind. The arrangement therefore gives four possible take-off and landing directions. The power system (Fig. 20) comprises a piston driven by compressed air at a maximum pressure of 150 kg./cm.² (2,130 lb./in.²) from an oleo-pneumatic accumulator. The air expands on the opening of a valve by a hydraulic jack, and thus oil passes under pressure into the cylinder. The piston pulls a heavy cable, by means of a primary reeving system, which pulls, by means of two secondary reevings, the cable towing the aircraft (Fig. 21). The total reeving ratio is 25/1. The towing hook is attached to the front part of the aeroplane at the apex of a tubular bracing (Fig. 22). The machine is held in catapult position by the hold-back link mentioned previously. For landing the NC.856 is equipped with a retractable hook (Fig. 23) which pulls the cable and piston in the direction opposite to that during take-off, thus returning oil to the recuperator and compressing the air.

*Produced by the Société Nationale de Constructions Aéronautiques du Nord.

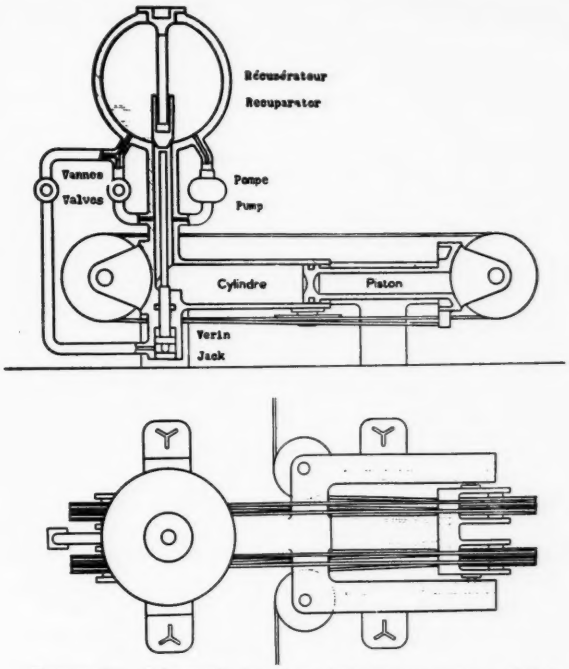


FIGURE 20. Schematic drawing of the power system of the Arbalète NC.856.

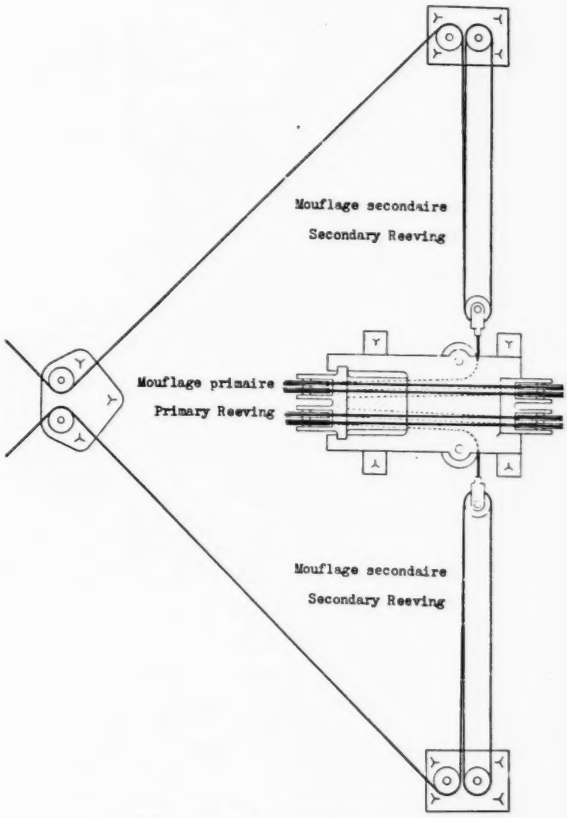


FIGURE 21. Diagram showing reeving unit of the Arbalète NC.856.

The following results were obtained:—

(*i*) Take-off in 22 m. (24 yd.) instead of 110 m. (120 yd.).

(*ii*) Landing in 14 m. (15·3 yd.) instead of 90 m. (99 yd.).

For the aeroplane in question (*see* Fig. 24), the installation requires only two strips of ground at 90°, 50 m. (55 yd.) long and 4-5 m. (13 to 16 ft.) wide. These strips do not need to be particularly level and a team of four men can install the Arbalète in two hours. To end this short discussion, it may be added that when the landing operation is not used to re-charge the power supply a small 4 cv. (4 h.p.) auxiliary motor can do this within two minutes.

CONCLUSION

In this NC.856 version, the Schneider-Fieux Arbalète reduces the equipment to a minimum and the very simple installation furnishes an ideal solution to the problem:—minimum maintenance, easy transportation by truck and low price per unit (a figure of 8 million francs (£8,000) has been quoted).

Moreover, for an artillery observation aeroplane, the launching rate of one every two or three minutes is ample, and each artillery unit would need only one installation.

What would be the probable result of using the Arbalète for combat aeroplanes? It is difficult to be very precise about this, particularly in view of the fundamental differences:—much heavier weight, greatly increased take-off and landing speeds, need for a trolley or track for the aeroplane wheels and higher launching rates*. Nevertheless, in making a comparison with catapults of the direct-drive type, like the Latécoère, it is reasonable to say that, for the same type of power, the launching rate—which is essentially determined by the time taken to re-charge the power supply—would be the same. Hence the number of units required for a given landing rate would be the same, and so would the overall dimensions, which are a function of the launching distance. On the other hand, the dimensions and weight of the power system would be less for the Arbalète, because of the reeving system. But this is precisely the point which seems to be the more difficult to solve.

*At a lecture given on 15th March 1955 at A.F.I.T.A., in Paris, M. Fieux said that he is studying a larger version of his Arbalète, the aim being to launch a 6 ton aeroplane at 150 m.p.h. M. Fieux said he is convinced that this goal may be attained, by utilising the same principles as in the Arbalète, *i.e.* by direct towing of the aeroplane running on the ground. With a maximum acceleration of 3*g*, the launching length would be 330 yd. and the basic quadrilateral side would be 130 yd. The time for recharging the accumulator would be one minute with a 500 h.p. engine.

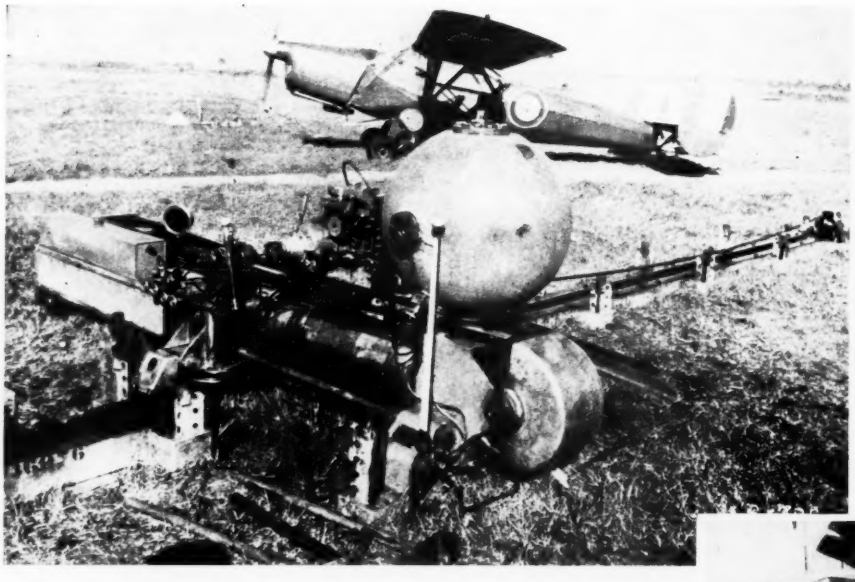
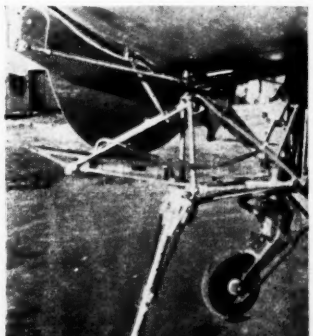


FIGURE 24 (*above*). General view of the Arbalète NC.856 aircraft and power supply.



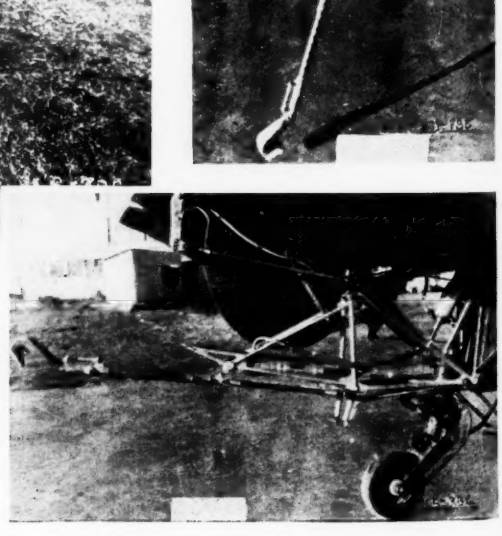


FIGURE 23 (*right*). Rear fuselage with arrester hook of the Arbalète NC.856. Up and down positions.

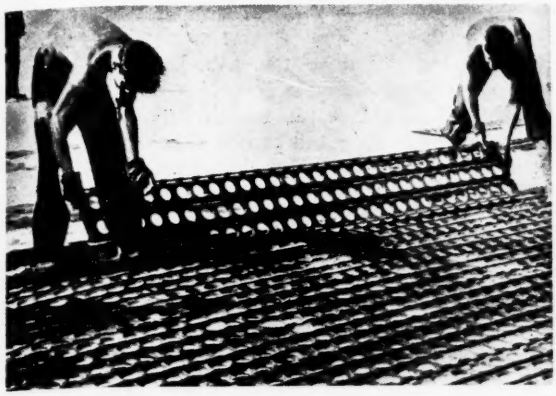


FIGURE 25. Laying pierced steel plank.

And although a single unit can be used for landing and take-off, it would be difficult to take advantage of this in practice when operating several units with rails and trolleys. It is more likely that separate units would be required for take-off and landing.

Thus, at the present stage of development, the two solutions are very similar, and from the point of view of ground loading, there is little to choose between them.

Metal Track

Before concrete runways came into use the first metal tracks were designed for use on rain-swamped airfields. Even before their adoption for aviation purposes, metal tracks were used to make soft ground firmer. Allenby's Army used them in this way to allow trucks to run more easily on the desert sand in the 1914-18 War.

From 1938, metal track was mass-produced in France. It was used only to improve certain parts of airfields, such as parking areas, taxi-ways and so on, and to lessen the effects of air raids by placing the track over filled-in bomb-craters. Each section consisted of iron sheet, welded on to cross-members measuring 1 m. × 5 m. ($3\frac{1}{4}$ × $16\frac{1}{2}$ ft.) and weighing 110 kg. (242 lb.), and the sections were bolted together.

In England, during the winter of 1939-40, an entire runway used by bombers was reinforced by a grid similar to that used for fencing. This simple solution unfortunately presented numerous problems, the chief being the difficulty of getting the grid to lie flat on the ground.

Meanwhile, after the beginning of the 1939-45 War it became obvious that increase in weight and in take-off and landing speeds were such that normal soil, even artificially strengthened, would not withstand continued use, and besides, in winter or in any bad weather many airfields would be out of action or, at least, would become dangerous. So, in 1940, the construction of concrete runways was started in England.

It was only much later, when battle lines moved more quickly, that metal track was used as a rapid means of constructing runways. Although it had not the strength and durability of concrete runways, metal track could be easily used on temporary airfields:—

(*i*) To distribute the wheel load over an area larger than the tyre contact area, thus allowing higher pressures to be used.

(*ii*) To delay deterioration of the ground due to wheel friction.

No attempt is made here to describe all the various types of metal track—there are about a dozen of them—which were used by the Allies between 1940-45. Reference is made to them in the Bibliography. The best known type is the P.S.P. (pierced steel plank) (Fig. 25).

THE PIERCED STEEL PLANK TRACK

Developed in the United States some time before that country entered the war, the P.S.P. was used in almost all theatres. Each panel consisted of mild steel sheet, pressed to a thickness of 3·5 mm. (0·138 in.), 0·38 m. (15 in.) wide and 3·050 m. (10 ft.) long, and weighed 26 kg./m.^{2} (5·3 lb./ft.^{2}). The panels were placed in rows with the longer side perpendicular to the direction of the runway and were joined at the side by bayonet-type fastenings.

ADVANTAGES AND DISADVANTAGES OF THE P.S.P. TRACK

This type of surface, which is easily mass-produced and simple to lay down, has two serious disadvantages. The ground under the track remains damp and, during bad weather, when the runway is being constantly used, mud and water are pushed up through the holes. The resulting accumulation of mud soon makes the runway unserviceable. To counteract this difficulty, and also that caused by dust in dry weather, the laying of straw between the ground and the track has been suggested. In addition, since the ends are not fastened, the panels have a tendency to rise at the ends if the loads are too great and this causes very dangerous projections.

The cost of building a metal track runway on suitable ground, that is, ground which is sufficiently firm (*e.g.* fine sand) and requires little or no preparation, is small compared to the cost of modern concrete runways. The track for a runway 2,000 × 50 m. (2,200 × 55 yd.) costs 120 million francs (£120,000) excluding labour and transport costs.

To build a runway of this length, 8,600 man hours are needed, which may seem short compared with the time taken for a concrete runway, but for rapid assembly a large labour force is needed. Time can be saved by previously assembling a track into 1,000 m.^{2} (1,200 yd.^{2}) sections and transporting them by truck; the complete runway could then be laid down in three or four days.

The possibilities of camouflage are good, except during the construction period. Damage from air attacks can be easily and quickly repaired, merely by replacing the damaged section. If, however, aircraft land before repairs have been made there is a strong risk of accidents caused by the twisted metal. The grids are recoverable and can be used again if the battle line moves.

FIGURE 26. The "Matador" on its launching cradle.

LIMITATIONS OF THE USES OF P.S.P. GRIDS

The load-bearing capacity of the grids is determined essentially by the nature of the ground on which they are laid. In the most favourable conditions (dry ground, sandy or stony soil) inflation pressures of 7 kg./cm.^{2} (100 lb./in.^{2}) and wheel loads of 12 tons are possible. On all other types of ground some preparation is necessary—drainage, a foundation of compacted sand and gravel of about 25-50 cm. (10-20 in.) thick. Such a runway requires the shifting of 30,000 to 60,000 tons of material and would take one month to complete.

The transportation of the required tonnage of track —about 3,000 tons for a 2,000 m. (2,200 yd.) runway— is a major problem of logistics.

Failing any other methods, metal track offers a quick solution but is subject to limitations which considerably reduce its value.

Launching from a Ramp

An aircraft launched by catapult must, before leaving the launching device or, in the case of the Arbalète, before leaving the ground, attain its minimum take-off speed. This condition, together with the maximum acceleration which the pilot can endure, determines the length of the catapult. In addition, the take-off clearance, beyond the ground run, is a function of the transition and climb performance of the aircraft, which depends upon the excess power available.

If, instead of being catapulted horizontally, the aircraft were launched along an inclined path (in the limit a vertical one) the restrictions are considerably reduced. The clearance of obstacles is obviously easier and the launching length is reduced by virtue of the inclined path, because the wing lift need only be a fraction of the weight, the proportion decreasing with increase of angle. In general when the aircraft leaves the guide rails, the speed should be sufficient to provide control effectiveness, *i.e.* about 100-120 km./h. (60-75 m.p.h.), particularly since the aircraft is gathering speed. Allowing an average acceleration of 3*g*, the launching length would be 15 m. (50 ft.).

The foregoing points define what is meant by launching ramps. They consist of a guide path along which the aircraft moves under the impulse of the take-off power of the engine, plus the additional rocket thrust. The machine can rest directly on the rails or on a trolley. The rockets can be attached either wholly to the machine, or partly to this and partly to the trolley, and they can be so positioned as to provide a component normal to the flight path, thus adding to the aerodynamic lift.

The additional force provided by the rockets is another essential difference between ramps and catapults, where the propulsive force is provided by the launching machinery.

Launching from a ramp has two major advantages over catapult launching:—

(*i*) A very small space is needed for the installation; it is no longer necessary to speak of "fields."

(*ii*) The launching device is very simple and it is smaller and lighter; it is easily transported and can be rapidly erected, and in the most effective direction; it can, moreover, remain on the vehicle used for its transport.

But these advantages must be paid for:—

(*i*) The rockets, whether liquid or powder, are still very expensive, of the order of 7,500 francs (£7 10s.) per ton of thrust per second, and since the thrust must be maintained until the aircraft has reached its normal climbing speed and after it has left the launching rails, this becomes very costly. It costs about 225,000 francs (£225) to launch a machine weighing 3½ tons with an acceleration of 3*g* for 3 seconds.

(*ii*) If, to camouflage the smoke produced during launching, an uncleared location were chosen, the landing would have to be made some distance away, involving transport and road clearing problems. If, on the other hand, the ramp were installed on the edge of a landing

FIGURE 27. Firing a "Regulus."

FIGURE 28. The SNCA-SE carriage (SE-1910) on its railway track. Propulsion is by liquid propellant rockets. The two nozzles which may be seen on the front are those of the braking rockets. The stub wings with negative incidence are for increasing carriage adherence to the track.

field, part of its advantage would be lost. In any case hoisting equipment is necessary to put the aircraft back on the ramp and for loading the rockets.

The launching rate could never be very high and several launching units would usually be needed. The supply and transport of the large number of rockets necessary becomes a difficult problem which would offset the advantage gained in the transport of the ramps themselves.

All these considerations indicate that launching from a ramp would be more suitable for guided missiles than for aircraft; in particular, the problem of their return would not apply. As regards the mobility of launching stations, this is not usually so vital for missiles as for air support action and the problems of organisation and supply are simplified.

So far there has only been one example of launching a piloted aircraft from a ramp; this was the German Bachem "Natter" in 1945. The ramp was vertical, 24 m. (80 ft.) high, the acceleration was 2·2*g* and the rate of climb about 180 m./sec. (35,000 ft./min.). Several launchings were made without a pilot, but the only piloted attempt had tragic results.

Vertical take-off is at present being studied in various countries and is developed from the same idea, but there is no ramp and no launching rockets. The aircraft takes off vertically because of the high power/weight ratio of the engine, and can be brought down in the same way. As mentioned earlier, this can only be a long-term solution because of the complex problems involved.

However, for guided missiles, launching ramps are currently in use, and the best known examples are the "Matador" and the "Regulus." The Matador is launched from a trailer bearing the supporting cradle (Fig. 26), which might almost be called a ramp because, in fact, there is no velocity of translation. The thrust of the launching rocket is inclined so as to be in equilibrium with the weight of the missile from the outset. The American Navy Regulus is launched on a genuine ramp at an angle of 45° by means of two rockets at the sides (Fig. 27).

Meanwhile, profiting from their experience with the Matador, the Americans are now planning to apply this same system to the launching of fighter aeroplanes. In the past few months successful attempts have been made to launch F-80's and F-84's using high-powered rockets. For landing, the Americans are developing the "cushioned mat" principle, devised in England and discussed more fully later.

Carriages on Railway Lines

We now return to horizontal take-off, but in this case the aircraft is supported on a carriage, usually self-propelled.

This solution is a natural development from the normal use of railway lines with the following advantages:—

1. The rails constitute a track which is able to take heavy concentrated loads and the laying of the track on any type of ground is established practice.
2. In wartime, the existing railway network could be used for the transportation of the carriages and the hoisting and maintenance gear necessary (as with heavy artillery).
3. The problem of directional control does not apply to a carriage on a railway track, as it does with one running freely on the ground.
4. As regards damage from air attacks, experience has shown that repairs can be effected very quickly (in a matter of hours) by the special services of the Army.

However, in practice, railways have not been used to launch ordinary piloted aircraft, with a few exceptions. The reason is that, as with the solutions already considered, the problem of landing remains. Also, launching from railway tracks combines all the disadvantages of the previous solutions; the problem of transporting the aircraft from its landing place to the railway and hoisting it back on to the carriage, braking the carriage, the high cost of rockets and supply problems, and greatly reduced mobility in areas outside the railway network because of the weight and size of the equipment. The launching rate is also limited by having to wait for the return of the carriage to the starting

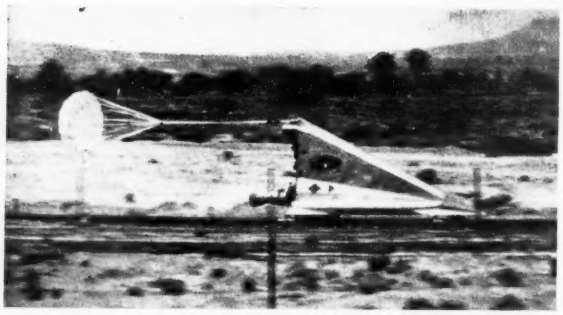


FIGURE 29. A test with a sledge on tracks at Edwards Air Force Base (California).

point, and here again several parallel installations would be necessary to provide the same take-off frequency as runways, with a consequent increase in the ground organisation needed and the chances of being seen from the air.

It is chiefly for practical experiment in the study of the innumerable problems arising from flight at different speeds that carriages on railway tracks have been used so far.

Although this application does not come within the framework of the present paper a few examples are given here, with some figures.

One of the first examples was used by Heinkels at Warnemunde in 1925 in launching two fighters, the HD 26 and HD 27. The launching ramp was constructed on firm ground and consisted of three rails on which ran the tricycle launching trolley. The height of the middle rail was adjustable so as to allow the angle of attack of the aircraft during the take-off run to be fixed in advance. There was no extra propulsive force and acceleration was provided entirely by the propeller. The aeroplane and carriage separated automatically, the carriage being stopped at the end of the run by a braking device. It was these first attempts which brought about the improved Heinkel launching scheme which was adopted by the Deutsche Lufthansa on the South Atlantic route.

At the end of the Second World War the Messerschmitt Me 163B rocket fighters were probably launched in this way. It seems, however, that the use of a carriage on a runway has been preferred as it is the best known; this is discussed again later on.

In France, carriages on rails have been built for experimental purposes. For example that of the S.N.C.A.-S.E. which, in trials held at Istres, reached a speed of over 300 km./h. (185 m.p.h.) and showed great stability (Fig. 28).

In the United States there are several such installations for the U.S. Air Force and the Navy in California and New Mexico (Fig. 29). At the Holloman base a speed of 632 m.p.h. was reached on a rocket-propelled sledge on rails with a pilot on board.

Take-off and Landing on Cables

In 1912, Louis Blériot, who probably had cause to remember some sudden and painful contacts with the ground, designed and constructed a take-off and landing device by aerial cable for one of his machines (Fig. 30). It consisted of a cable supported by pylons some height from the ground and the aeroplane released itself as it gathered speed. It was retrieved by passing under the cable to which it was re-attached with the aid of a lyre-shaped arrangement as it climbed. A braking device on the cable retarded its travel.

A similar system was used by the Americans in the Second World War. Designed by Captain James H. Brodie, of the Army Air Force, it was used successfully from 1942 for the Stinson Sentinel observation aeroplane, both with ground installations in the Pacific Islands and on cargo boats (Fig. 31).

One of the differences between this system and that designed by Blériot was the way in which it was hooked

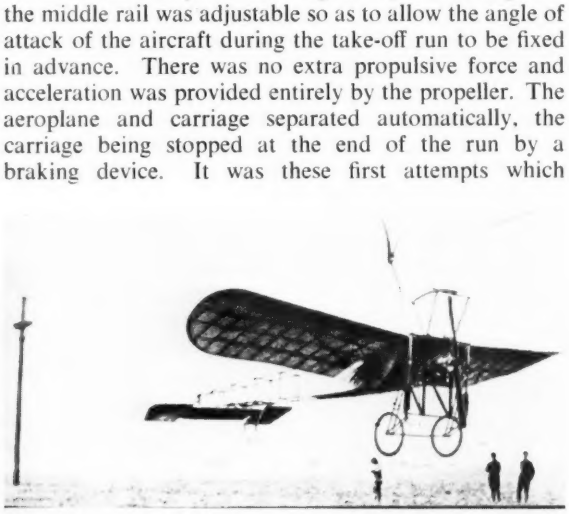


FIGURE 30 (*left*). A device designed by Louis Blériot and flight tested by Pegoud in 1912, for take-off and landing on an aerial cable.

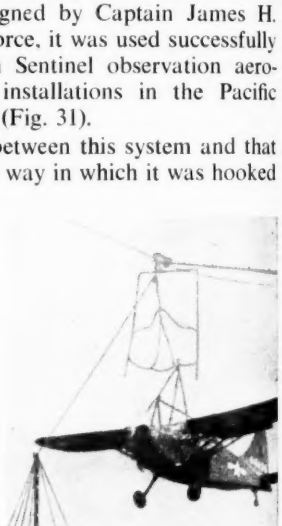


FIGURE 31 (*right*). The Brodie System. The pilot of an L-5 about to snag the nylon landing sling loop with the aeroplane's hook.

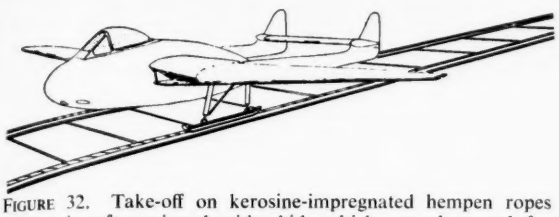


FIGURE 32. Take-off on kerosine-impregnated hempen ropes of an aircraft equipped with skids which are also used for landing (D.O.P. system). Design study for a Mistral interceptor aeroplane.

to the cable; the hook was snagged on a nylon loop hung from the cable, instead of the lyre-shaped arrangement engaging the cable from underneath.

The cable take-off system designed a few years ago by M. Renollaud, of the French D.O.P. Company, is very different. M. Renollaud, who has for a long time studied the problems of eliminating undercarriages, has provided details of his investigations from which the following information has been obtained and for which the author wishes to thank him.

The Renollaud-D.O.P. system applies essentially to aircraft equipped with landing skids. As these are treated separately later, only take-off is discussed here.

Among several variations, the system studied in most detail was as follows:—

A light iron track is laid on the ground (Fig. 32). The rails are made with grooves which fit the aeroplane skids and along each groove lies a hempen rope, 35 mm. (1·4 in.) in diameter, impregnated with kerosine; the aeroplane skids are also grooved lengthways, the cross section being semi-circular, corresponding to that of the cable. During the take-off run the machine slides on the cables which act as guides. A pipe at the front of each skid pours kerosine into the grooves and thus the runway is lubricated by the aircraft itself. The theory of this arrangement has been carefully studied by M. Renollaud; the coefficient of friction of the chrome steel skid on the kerosine-impregnated rope—which several tests showed to be the best combination—is 0·08 (the coefficient of a high pressure wheel is 0·03 and of a very low pressure wheel is 0·12). The effectiveness of the guiding system, which determines the lateral stability, is excellent. Finally, there was no wear, either to the rope or the skid, after a number of launchings corresponding to considerable use. On this basis, M. Renollaud designed a practical application of his system to the Mistral fighter with a Nene turbo-jet. The following results were obtained:

Skids—Dimensions: 2 m. × 0·14 m. (6½ ft. × 5½ in.). Steel chrome flanges.
Weight of one skid: 35 kg. (77 lb.).

Total weight of the undercarriage: 240 kg. (530 lb.).

Length of take-off run on kerosine-impregnated rope: 647 m. (707 yd.) compared with 588 m. (642 yd.) with high pressure tyres, an increase of about 60 m. (65 yd.).

CONCLUSION

As with all schemes which need a fixed installation, the number to be built depends on the take-off frequency desired. It seems, however, that for the same frequency the D.O.P. system needs a smaller number of launching units. The length is about the same as that of an ordinary runway for the same type of aircraft. If take-off rockets were used, the run could be shortened, thereby reducing the weight of the installation. Finally, the possibilities of camouflage are very good and the same piece of ground can be used for take-off and landing, the grooves being sunk into the ground with only the cable projecting.

Although the D.O.P.-Renollaud system has not been put into practice, several interesting results were obtained relating to aircraft equipped with skids, and the development was a step towards a completely independent solution which is discussed later.

Ground Braking and Belly-Landing Devices

The question of tyre pressure is not of such primary importance to landing as it is to take-off. On a 1939 type of airfield, which could usually support pressures of 3·5 kg./cm² (50 lb./in.²), an aeroplane with a tricycle landing gear and high pressure tyres can land without damage. The wheels make furrows in the ground which help to brake the machine more rapidly than on a hard runway, but, because of these furrows the aeroplane is not able to take-off again and has to be transported to the nearest airfield with a runway. This leads to research on methods of take-off without a runway. Thus, the problem of landing modern aircraft might be expressed as follows: "If a catapult system is devised so as to eliminate the need of a field for take-off, at the same time another scheme must be devised to allow the aeroplane to land, also without a landing field or in as small a field as possible."

In this respect, the flight decks of aircraft carriers have proved that solutions to this problem can be found. A scheme has been suggested using a network of cables wound on braking winches which are picked up by a

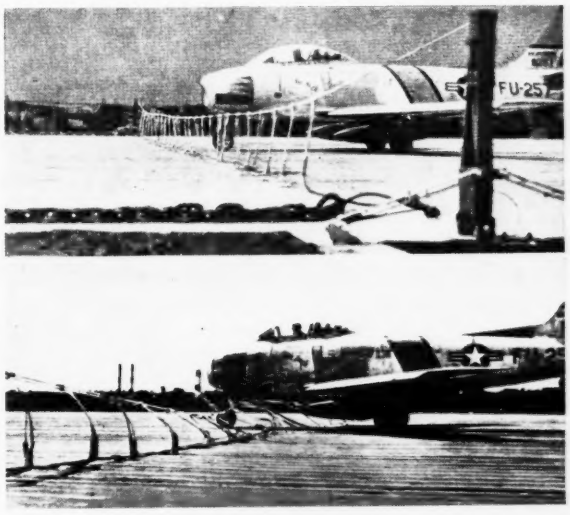


FIGURE 33. Landing barriers. *Top*: An F-86 about to make initial contact with nylon webbing of the barrier, and, *below*, when crossing it.

hook at the tail of the aircraft as it lands. Such a device was installed a few months ago in the United States at Lambert St. Louis Field, the aerodrome used by the McDonnell Aircraft Corporation. The braking system of the Arbalète is another example of such a solution.

Another related solution is that of cable web barriers. Used first on aircraft carriers, they were later extended to land bases, first in Korea and then to other aerodromes (Fig. 33). The web can be retained either by heavy chains each side of the runway, as shown in the photographs, or by compressed air cylinders, a solution which has the advantage of not requiring man power to replace the chains after each landing. Meanwhile, because of the high dynamic loads and cable-braking loads, the undercarriages of carrier-borne aeroplanes are subject to considerable fatigue, which adds greatly to their weight. Devices have therefore been sought which permit very short landing runs but which avoid undercarriage fatigue; this leads to belly-landing, used by landplanes in forced landings after failure of the undercarriage lowering mechanism. These considerations have led to artificial landing surfaces, tried out a few years ago in Great Britain, and recently in the United States.

The solutions discussed apply to jet aircraft, the presence of a propeller making belly-landing impossible in these conditions.

LANDING ON A SUSPENDED FLEXIBLE PLATFORM

At first it was proposed to construct a flexible platform from a sheet of reinforced rubber suspended some distance above the ground. The inertia of this platform was of great importance for it was found that when the aircraft descended vertically, the energy was absorbed first by the inertia itself and only later, as the aircraft sank down, by the supports. By a careful calculation of the strength and tension of the platform an excellent shock absorber could be constructed with an efficiency of more than 80 per cent. Moreover, by the appropriate design of the underside of the aeroplane it is possible to eliminate bounce entirely.

The advantage of this over similar systems is that the load can be greatly increased before any appreciable sinking results. With the normal landing speeds and size of platform, almost all the energy is absorbed by the platform inertia. To obtain good results the platform must be able to take very high initial loads, which should automatically be possible with rubber-base materials, and reasonable deck widths, necessitating in any case high pre-loading forces.

If steel nets were used as platforms, springs would have to be attached to the supports to obtain the necessary resilience.

LANDING ON INFLATED CUSHIONS

Another method, based on the "cushion" principle, has been tried by the Royal Navy using a Sea-Vampire, first on land and later on aircraft-carriers.

In this case the landing platform was made up of a series of inflated reinforced rubber cylinders, 1-1·20 m. (33-40 ft.) in diameter.

The machines approach at greatly reduced speed with hook extended, wheels retracted, and in a tail-down attitude. The hook catches an arrester cable stretched a little above the mattress and the aircraft "stalls" immediately on to the latter. The aircraft is stopped in a few yards and a normal airframe can take the loads with a few reinforcements on the underside. Deceleration is severe, as much as 8 to 12g during trials. With most aeroplanes the jet engine must be cut, either voluntarily or automatically, by means of a device which comes into play either when the aircraft lands or when it decelerates, to avoid deterioration of the mattress caused by the jet efflux.

These devices are of great interest, both to simplify the landing of carrier-borne aircraft, and to extend to other types of aircraft this method of landing on a very soft platform without elaborate ground equipment. After a trial period in Great Britain in about 1951, work on this scheme seems to have stopped, perhaps because of the fundamental difficulties of rapid deterioration and the high cost of repairs.

Again, one of the chief problems is the rapid removal of an aircraft without an undercarriage, which requires tractors or cranes near the landing area.

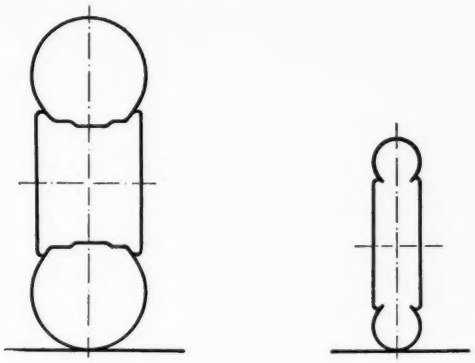
Meanwhile, it has been announced by the Press that the study of landing on cushioned mattresses has recently been resumed in the United States in connection with the landing of aeroplanes from the Matador ramp.

Low Pressure Tyres

It may seem at first sight that the simplest method of eliminating runways would be to use aircraft with low pressure tyres similar to those on the all-purpose military automobiles of V.L.R. type*. To define first what is meant by low pressure tyres—the French official specification thus designates tyres with a maximum effective pressure less than 5 kg./cm.^{2} (71 lb./in.^{2}). In fact if all types of ground are to be used (meadow land, cultivated land, beaches, and so on), experience shows that tyre pressures of about 2·5 kg./cm.^{2} (35 lb./in.^{2}) would be needed to keep the ground contact pressure to a reasonable level (in effect the contact pressure is slightly higher than the inflation pressure because the tyre walls support some of the weight. These pressures would be equal only if the tyre were perfectly elastic). But since the tyre is, in principle, only a cover, it is compressed air which supports the weight and impact loads, if the slight elasticity of the walls is neglected. Also, to sustain a given load and to absorb a given amount of energy, there is a choice between a large volume of air at low pressure and a small volume at high pressure. A large volume of air involves a larger tyre and hence more weight as well.

Figure 34 shows the difference between the two solutions. In the upper diagram are two wheels, both of which will support the same static load of 3,650 kg. (8,047 lb.); the one on the left is at 3 kg./cm.^{2} (43 lb./in.^{2}) and weighs 53·3 kg. (117 lb.); that on the right is at 16·5 kg./cm.^{2} (235 lb./in.^{2}) and weighs

*V.L.R.—Voiture Légère de Reconnaissance. A French truck similar to an American Jeep.

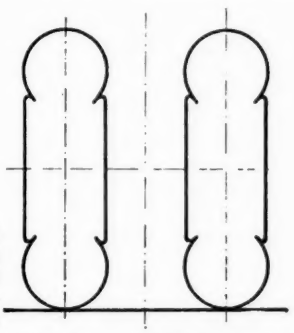


Pressure: 3 kg/cm.² (43 lb./in.²)
Static load: 3,650 kg. (8,047 lb.)

Weight:	kg.	lb.
Tyre	32	70·5
Tube	5	11·0
Wheel without brake	16·3	35·9
Total	53·3	117·4

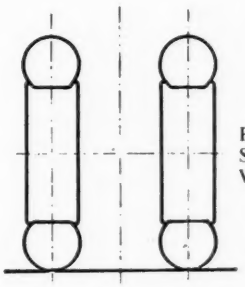
Pressure: 16·5 kg/cm.² (235 lb./in.²)
Static load: 3,650 kg. (8,047 lb.)

Weight:	kg.	lb.
Tyre	9·20	20·2
Tube	1·45	3·2
Wheel without brake	11·13	24·6
Total	21·78	48·0



Pressure: 4·9 kg/cm.² (70 lb./in.²)
Static load: 3,628 kg. (8,000 lb.)

Weight:	kg.	lb.
Tyre	46·8	103·3
Tube	7	15·4
Wheel without brake	47·8	105·3
Total	101·6	224·0



Pressure: 11·2 kg/cm.² (159 lb./in.²)
Static load: 3,810 kg. (8,400 lb.)

Weight:	kg.	lb.
Tyre	27·3	60·2
Tube	3·4	7·5
Wheel without brake	34·8	76·6
Total	65·5	144·3

FIGURE 34. Comparison of low pressure and high pressure wheels.

21·8 kg. (48 lb.). The lower diagram shows a specific example of twin wheels on a modern aircraft designed recently with low pressure tyres (left) and high pressure tyres (right); here the difference in pressures is less than in the previous example but the differences in size and weight are still considerable.

These two examples show clearly that with retractable undercarriages low pressure tyres raise a difficult problem. If they retract into the fuselage it is necessary either to increase the diameter and consequently the drag coefficient, or to reduce the fuel capacity or the payload or bomb load. If they retract into the wing, assuming that the thickness ratio will allow this, the result will be an increase in weight or a decrease in wing stiffness. Lastly, if the wheels are only partially retracted, the external wheel wells would result in reduced speed and, on high speed aeroplanes, disturbance of the air flow would aggravate compressibility troubles. In any case, increase in weight is inevitable.

Because the size of a single low pressure tyre would be prohibitive, twin and quadruple wheels have been suggested. With heavier aircraft, or where space is not so limited, this solution has undeniable advantages. But the problem is not as simple for fighter aeroplanes where, with the possible exception of weight, all the disadvantages already mentioned still exist.

It is easy to understand why aircraft designers, compelled to satisfy General Staff requirements, choose the most simple solution—at least from their point of view. It is not therefore surprising that improved performance is accompanied by increased tyre pressure.

Caterpillar Track Gear

HISTORY

Thirty years ago when the problems of runway length and tyre pressure had not yet arisen, different considerations led to research on the adaptation of caterpillar track gear to aeroplanes. The object was to allow aircraft to use any type of ground, provided that it was reasonably horizontal and unobstructed, without first levelling it and draining it; and to do so without additional ground equipment. Caterpillar tracks fitted to all-purpose vehicles had shown their possibilities during the First World War and also in the Colonies. Such vehicles were able to travel over bumps and ruts as well as on soft and swampy ground—conditions which would be impossible for wheeled vehicles.

At almost the same time, in France and in Italy, two research workers attempted the application of caterpillar track gear to aircraft. In 1927, a very simple device, closely allied to the orthodox caterpillar gear used for all-purpose vehicles was conceived by Chevreau, built by Louis Vinay and successfully tested by Peuillot on a Gourdou-Leseurre monoplane (Fig. 35), but this scheme was never followed up.

In Italy, Count Bonmartini worked on the same problem from 1928 onwards. In 1951, in the Salon de Paris, he exhibited a Piper Cub with a caterpillar track (Fig. 36), and at about the same time his scheme was

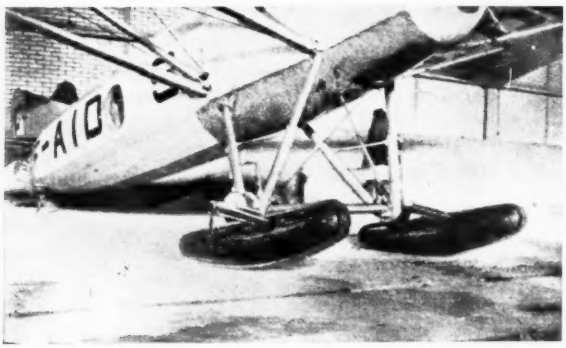


FIGURE 35. 1927. The Loire-Gourdou-Leseurre aircraft fitted with track gear skids manufactured by Louis Vinay.

used on English and American light aeroplanes in Italy and Switzerland.

In 1940, a Dowty caterpillar track was fitted to a Westland Lysander but, because of other priorities, was not developed. During the war, Fieseler built a model very like the Bonmartini system but, as with the Lysander scheme, other urgent needs prevented its development. A solution similar to that of the caterpillar track gear was effectively used by the Germans on the Messerschmitt 323 troop carrier (Fig. 37). This machine had a fixed landing gear with ten wheels in tandem, five on each side of the fuselage. These wheels, independent of each other, were elastically mounted. Such an undercarriage rode over irregular ground in much the same way as a caterpillar, but the system had many disadvantages—increased weight and size, rapid tyre deterioration, and retraction was virtually impossible*.

Meanwhile, after the war, it was realised that the need was urgent to provide military air transports—troop carriers, or aircraft for the supply of advance columns and encircled formations—which were not only independent of runways but which could use airfields in bad condition and in all weathers. General Guderian, as mentioned earlier, attached particular importance to this aspect of modern warfare and, as a tank specialist, naturally supported the use of the caterpillar track.

In 1948-49, the Boeing and Fairchild Companies in the United States developed and built caterpillar track gear for the B-50 and C-119 (Fig. 38). Take-offs of 54 tons were achieved with the B-50 and on the whole the trials were encouraging. The Fairchild Company received an order for 15 machines with caterpillar tracks, but it seems that this order was never fulfilled. The difficulties connected with their use were no doubt the cause, and these are now briefly described.

TECHNICAL CONSIDERATIONS

From a technical point of view, caterpillar track landing gear is characterised by the replacing of one or several wheels by a track made of a rubber belt, usually

*Another German military transport, the Arado 232, had, in addition to a normal tricycle undercarriage, 11 pairs of small wheels in tandem under the fuselage, to allow the aircraft to operate on soft or uneven ground.

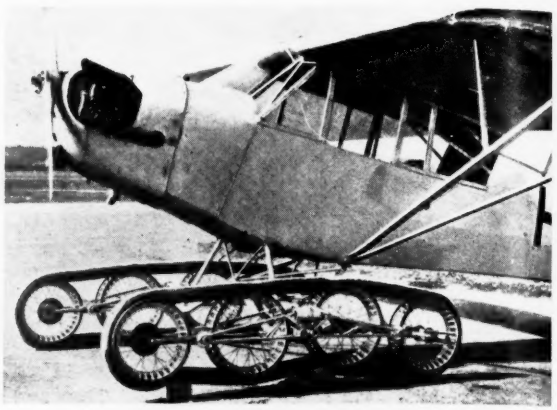


FIGURE 36. 1950. A Piper Cub fitted with Bonmartini track gear. The track gear can be seen running over experimental obstacles.

reinforced by a strong web, and guided by a rather complex system of rollers (Fig. 39). Such a system may be either rigid or articulated. Only the Vinay device was rigid and could be fitted without modification in place of the wheel. In practice it provided very poor shock absorption.

The modern tendency is to increase the number of articulated joints and separate shock absorbers so as to reduce as much as possible the local stress of impact. All the rollers are elastically mounted independently of each other, so as to support the tread while allowing sufficient deformation. The Bonmartini system has a fairly narrow belt which involves comparatively heavy ground pressure for this type of landing gear. On the other hand, for the Fairchild, the static pressure is less than 1 kg./cm.^{2} (14 lb./in.^{2}) and the dynamic pressure no more than 1·8 kg./cm.^{2} (26 lb./in.^{2}). It was about 3·5 kg./cm.^{2} (50 lb./in.^{2}) on the Boeing B-50.

In operation, the rear rollers support most of the load, the front roller being used to surmount the

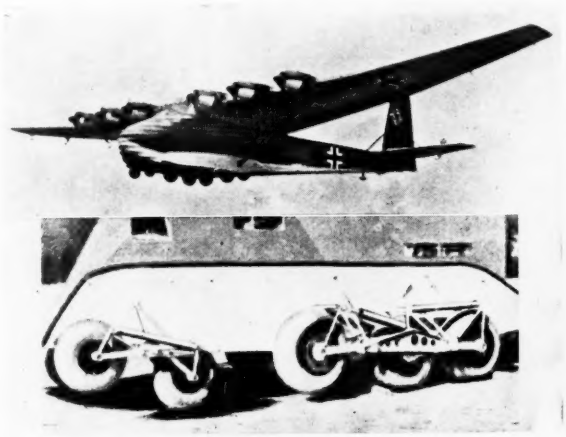


FIGURE 37 (*left*). The Messerschmitt 323 troop-carrier fitted for operation on rough grounds with ten-wheeled undercarriage, details of which can be seen on the lower picture.

obstacles. Trials in the United States have shown that in a strong side wind the belt tends to come off the rollers, in spite of the guiding grooves, and is damaged on the supports or on the flanges. Besides, some difficulties, for which solutions have been found, arose with the question of braking: on landing, excessive braking of the rollers may lock the track: after take-off, braking is not desirable because it puts considerable stress on the structure. Also, retraction is more difficult than with ordinary wheels. Finally, the installation is heavier and the rolling friction greater; this is an advantage when landing but not for take-off.

CONCLUSION

The results and experience gained so far show that caterpillar tracks offer an interesting solution, mainly for the two types of machine which must be able to use rough ground:—

(*i*) Light reconnaissance aircraft; because they are relatively slow, the drag increase would not be too serious; the Bonmartini system seems the most suitable.

(*ii*) Troop-carrying aeroplanes; being relatively heavy, a slight increase in empty weight is allowable if this gives a marked increase in their operational value. The best solution is the American type, but there is still the problem of landing and take-off in a cross wind. The addition of some freedom in rotation to the main caterpillar undercarriage would solve the problem, but involves serious practical difficulties.

There is no doubt that undercarriages of this type would cost considerably more that wheeled types, and their maintenance would be more complicated. But it is well to remember at this point the cost of construction and maintenance of concrete runways.

Skis and Skids

HISTORY

At the beginning of this paper it was recalled that the landing gear of the Wright Brothers' machine consisted of two long wooden skids. To justify the word "landing gear," they were used only in landing, and not for take-off. They provided the obvious solution for landing on the sandy ground where the first trials were held. Other aircraft of this "époque héroique" were similarly equipped, in addition to wheels, with skids curved at the front, but these were solely to prevent overturning.

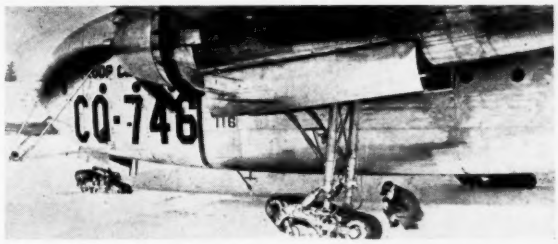


FIGURE 38. The Fairchild C-119 fitted with a track gear, on a snow field.

In 1918, the British Navy, in trials on the "Furious," fitted a Sopwith biplane with landing skids instead of the usual wheels which were giving trouble in cross winds (Fig. 40). The trials were highly satisfactory and, in addition, the aeroplane proved to be able to take-off from a grass landing-field quite as well as the wheeled version.

Later, when aircraft were being built for operation in snow-covered areas, the wheels of the undercarriage were replaced either by long straight skids or by skids which had a greater load per unit area but were far more compact.

In certain cases, where aircraft have to operate sometimes on ordinary ground and sometimes on snow, undercarriages with combined wheels and skis are fitted. On firm ground the wheels alone support the aeroplane; on snow, the wheels start to sink in, and then the skis support the aeroplane. The Hanriot 431 was equipped with such an undercarriage (Fig. 41).

On ground which is not snow-covered, skids, which have a high coefficient of friction, have been used for landing—by gliders, launched by towing. At the end of

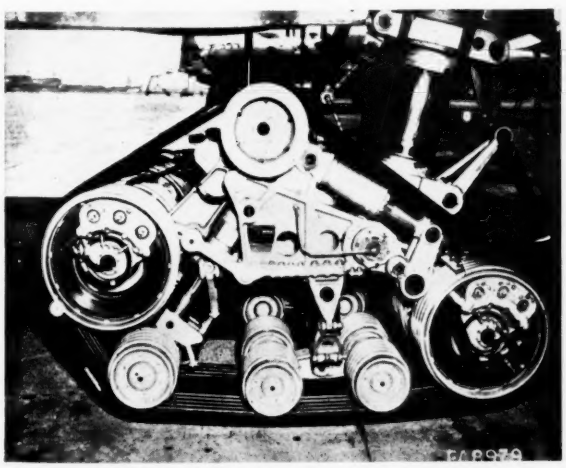


FIGURE 39. Main track gear unit of Boeing B-50.

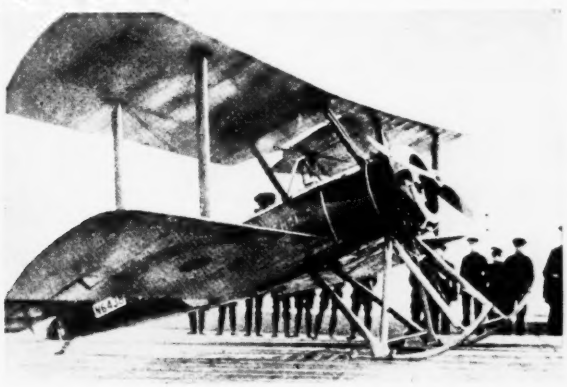
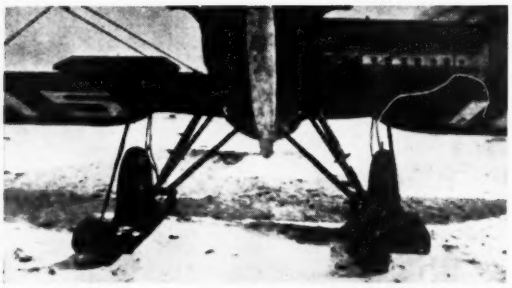


FIGURE 40. 1918. The Sopwith Pup with a rigid skid undercarriage.



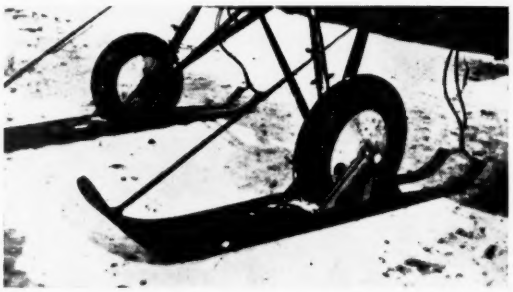


FIGURE 41. 1931. Hanriot 431 aircraft. Combined wheels and skis undercarriage.

the Second World War, two German machines, the Arado 234A, which was never in quantity production, and the Messerschmitt 163B, were designed to take off from a trolley.

Why were these two machines equipped in this way? With the Arado 234 it was not a question of the length of the runway. Professor Blume, the creator of this machine, wrote to the author on this subject: "The reason why skids were chosen for the Arado 234A was that this system allowed more fuel to be carried in the fuselage, since the aeroplane, being a reconnaissance aircraft, had to have a long range. At first, only a small number of these were to be built and since they were to be used in isolated cases the additional expense of using a launching trolley could be justified. But when the aircraft came into use as a bomber, the trolley scheme was abandoned and replaced by a tricycle undercarriage for the 234B."

With the Messerschmitt 163B, a short-range rocket-powered interceptor, it is probable that the requirements of minimum weight and size led to the skid-trolley solution.

Figures 42 and 43 show these two machines.

From time to time, since the end of the Second World War, aircraft designers have tried the skid-trolley system, but it has been confined either to experimental aircraft, to reduce size and weight as much as possible (*e.g.* the rocket-powered Northrop P-79 of 1945)—or else to target aircraft, for the same reasons (*e.g.* the Australian Jindivik—Fig. 44). The McDonnell XF-85 parasite fighter was equipped with a ventral ski allowing it to land safely if it missed re-connection with the parent aircraft.

The Baroudeur was the first example of the use of skids on a combat aeroplane as the normal means of landing. The reason for this was simply to avoid the use of runways (Fig. 45). This machine is considered in more detail later. Meanwhile, the use of skis on seaplanes is discussed briefly.

The possibility of obtaining increased hydrodynamic lift by the use of water-skis, as demonstrated by those who practise this aquatic sport, has already been applied to aviation by Canadian pilots. They have claimed that their machines, equipped with ordinary snow skis, can slide across marshy ground or muddy beaches to the water and will then rapidly attain take-off speed. On return, they land some distance from the coast and proceed to their berth, in shallow water, at a speed sufficient to maintain the lift of the skis.

The application of hydro-skis to the Sea Dart fighter is well known. Here, the machine is essentially a seaplane with a water-tight hull. It takes off and lands on retractable skis, which results in a better hull shape and

FIGURE 42. 1943. Arado 234A twin jet reconnaissance aircraft. Take-off on tricycle trolley. Landing on central main skid, with auxiliary skids under nacelles and tail skid.

FIGURE 43. Messerschmitt Me.163B. Take-off on twin wheels; trolley jettisonable in flight and landing on retractable central skid.

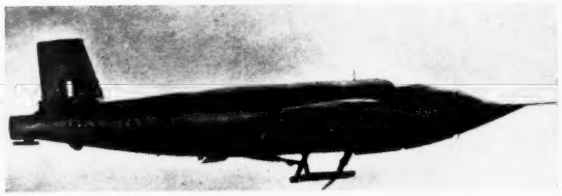


FIGURE 44. 1952. Jindivik pilotless target aircraft lands on a central skid retracted during the flight.

FIGURE 45. The Baroudeur landing.

probably much less weight (Fig. 46). There is an additional advantage in the possibility of this seaplane landing on ordinary ground and manoeuvring by means of little wheels at the ends of the skis.

Surface Conditions for the Use of Skis

On snow, the coefficient of friction of the skis, made either of wood or metal, is very small and may even be less than the best value for wheels (about 0·03) which could result in shorter take-off runs than with wheeled undercarriages. The disadvantage lies in the tendency to ground looping and in the lack of resistance to side-slip in a cross wind. It might be possible to arrange the load on the skis so that they would sink in far enough to avoid sideslipping, but if this were carried too far, piling up of snow would result, with a consequent increase in take-off resistance. To obtain skids with low drag at take-off and good braking characteristics on landing, they can be hinged about an inclined axis so as to be parallel to the direction of motion at take-off and inclined obliquely, as snow ploughs, on landing (like a reversed "stemmbogen") (Fig. 47).

On any type of ground: The coefficient of sliding friction is generally higher than the coefficient of rolling friction of wheels, so that the landing distance is less for an aircraft on skids than for an aircraft on wheels not using brakes. Special precautions must be taken to disperse the heat produced by friction (increasing the surface of radiation and isolating it from the rest of the structure). For braking, a coefficient of friction of 0·8 is the highest possible with wheels, but the coefficient is practically unlimited if braking is achieved by means of claws dragging in the ground. Thus the ground manoeuvrability obtained by differential braking with skids is comparable with that obtained on low pressure wheels.

CONCLUSION—THE POSSIBILITIES OF THE SCHEME

The main advantage presented by skis and skids lies in the possibility of obtaining very low ground pressure: 1 kg./cm.^{2} (14 lb./in.^{2}) on the Baroudeur. Also, it is possible to use unprepared ground as an airfield, even ploughed land or swampy ground, which would be impossible for aeroplanes with wheels. As already indicated the same advantage applies to

FIGURE 46. The Convair Sea Dart.

caterpillar tracks, but the skid solution is simpler, lighter and less bulky.

The use of skids for take-off is related to the thrust/weight ratios available and the corresponding coefficients of friction. For stony ground (as at Istres) or a dry clay surface (Toulouse in summer) the coefficient of friction varies from 0·25 to 0·3. On slightly damp turf-covered ground the coefficient of friction is between 0·10 and 0·15 (the coefficient of friction for low pressure wheels is about 0·12). Direct take-off on skids is certainly feasible for jet fighter aircraft, because of the high thrust/weight ratio, as the Baroudeur trials have proved.

During landing, skids have the advantage of being able to absorb part of the energy of impact, either by sinking into the ground or by using the lateral component of friction (the Baroudeur skids are hinged about a longitudinal axis).

Since skids lend themselves particularly to streamlining it is possible that retraction will become unnecessary, giving a reduction in weight and increased safety.

Preliminary experiments have shown that the coefficient of friction of skids can be greatly reduced by applying moisture to the ground. It is probable that the injection of water under pressure (by means of a compressed air bleed from the engine) between the skid and the ground would reduce the coefficient of friction to the value for low pressure wheels.

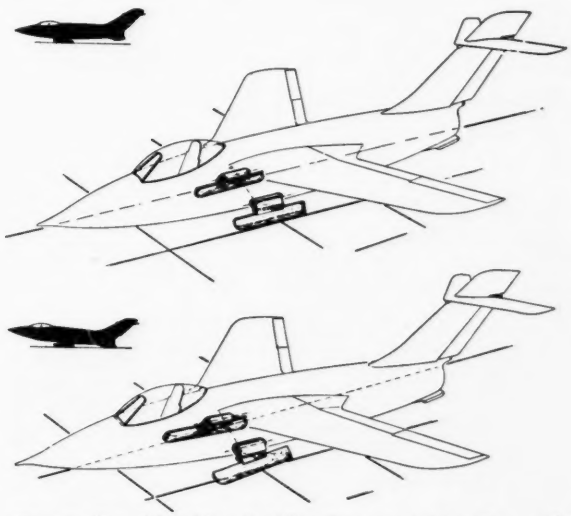


FIGURE 47. Skids hinged obliquely are, at take-off, parallel to the direction of motion (*top view*) and, at landing, divergent looking forward (*lower view*).

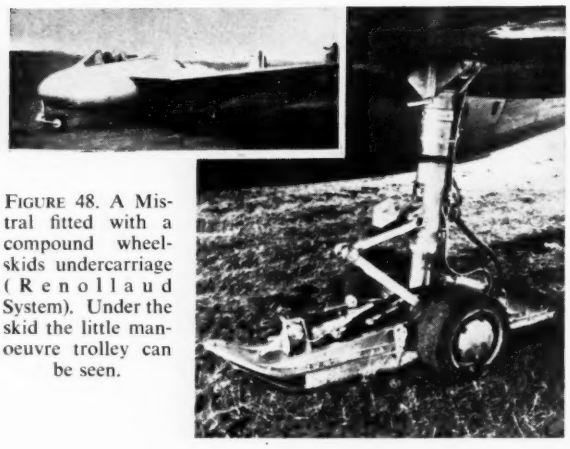


FIGURE 48. A Mistral fitted with a compound wheel-skids undercarriage (Renollaud System). Under the skid the little manoeuvre trolley can be seen.

The Wheel-skid Solution

Skids, like the caterpillar track, result in very low ground pressures, but they are lighter and simpler. On the other hand, ground manoeuvrability is not so good because of the higher coefficient of friction. Except during the take-off period for aircraft with high thrust/weight ratios, an auxiliary trolley is needed to manoeuvre the aircraft on the ground. To avoid this limitation, a combined wheel-skid solution might be possible. This solution could be applied to all configurations, having regard to the position of the wheel and the skids with respect to the centre of gravity of the machine.

One example of such a scheme has been developed by M. Renollaud, of the French D.O.P. Company, whose work was referred to earlier, and has been applied to a Mistral fighter. The front wheel of the standard machine was retained but was fitted with a very low pressure tyre.

The skids were shorter than in the cable take-off version, and each was provided with a claw allowing differential braking. The jet thrust produced a moment which reduced the load on the skids, and hence the sliding friction.

For ground manoeuvring, particularly when the engine is cut, a small twin-wheel trolley is placed under each skid (Fig. 48). This scheme was successfully tried out in France in January 1955.

FIGURE 49. 1927. The undercarriage of the Nungesser and Coli aircraft l'Oiseau Blanc jettisoned after take-off (Avions Pierre Levasseur).

The Multi-Terrain Undercarriage

Of all the take-off systems envisaged, either for shortening the take-off length or for avoiding the use of runways, the multi-terrain undercarriage is the least dependent on ground equipment. In principle, the system follows the early ideas of separating the parts of the aircraft used for take-off from those necessary for flight. Some earlier naval aircraft, such as the Pierre Levasseur PL10, were able to jettison their undercarriages in flight before an emergency landing on water. Some long-range aeroplanes, like the "Oiseau Blanc" of Nungesser and Coli (Fig. 49), were also able to jettison their undercarriages. The naval aircraft used replacement undercarriages for taking-off again, which was not too difficult in view of the simple undercarriages of that time. The intruders were forced to belly-land on return.

Consider the following solution:—instead of a jettisonable undercarriage, build a sturdy but light trolley, with low pressure tyres and efficient suspension. The aircraft, instead of belly-landing, has fixed or retractable skids. The result is a composite all-terrain aeroplane undercarriage, a solution which, for certain types of machine, offers the best compromise between airborne and ground requirements.

Examples of this type have already been mentioned, for example the Messerschmitt 163B, and it was explained that their use of the skid-trolley solution was not a result of the runway problem. The Canadian de Havilland Beaver is also of interest. Built at the de Havilland factory in Toronto, it had to be delivered to a neighbouring stretch of water. To avoid transportation by road and complicated manoeuvring, a taxying trolley was used for take-off from the factory (Fig. 50).

TECHNICAL DIFFICULTIES OF THE TROLLEY ARRANGEMENT

In addition to being sturdy but light, as mentioned earlier, the trolley must also meet other requirements connected with its *permanent* role and its operational use.

FIGURE 50. The de Havilland Beaver seaplane taxying carriage.

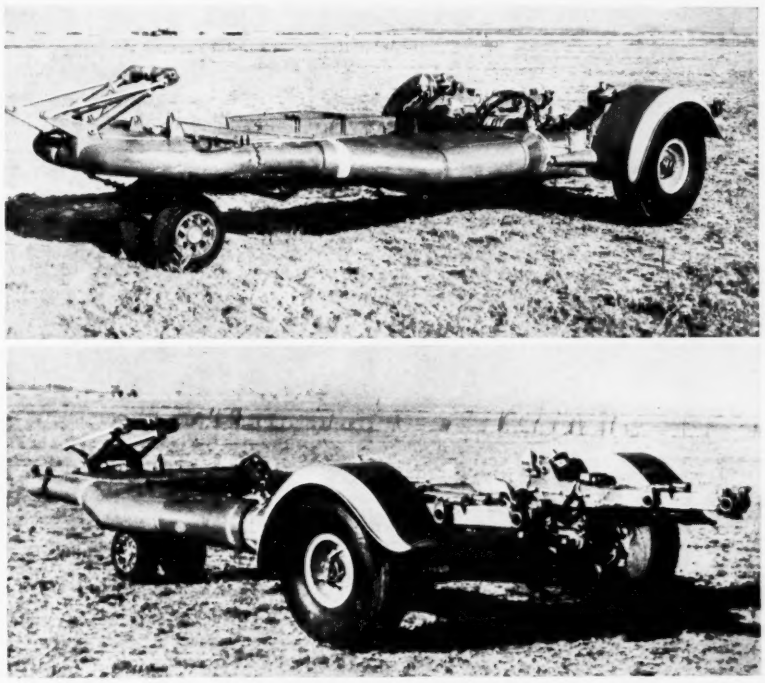


FIGURE 51. The take-off trolley of the Baroudeur.

The combined trolley and aeroplane must be directionally stable, must ride smoothly, and be manoeuvrable by the pilot at all speeds. The upper surface of the carriage must not foul the aircraft during separation (which may take place in a cross wind). The trolley must remain directionally stable after separation, whether or not brakes are applied, and must not initiate porpoising, whatever the speed and ground condition.

To be able to use the shortest possible take-off space, the trolley must be designed to carry the take-off rockets and to include a braking device which works automatically, but not immediately after separation from the aircraft. During the firing of the rockets mounted on the trolley, a safety device must prevent the accidental release of the aeroplane. The trolley must be either self-propelled or easily towable by a vehicle such as a jeep. The jeep is certainly the easier, and also less expensive because deterioration of the engine unit would result from the repeated shocks to which the trolley would be subjected.

Lastly, the aircraft must be hoisted on the trolley, or lowered from it, with a minimum of work; here also the jeep can provide the engine power. During the hoisting operation, the relative positions of trolley and aircraft must allow for ground irregularities and for lack of precision in positioning the trolley.

The development of devices to fulfil these conditions involves a long experimental programme. With the Baroudeur, which is now discussed, these experiments were conducted systematically, first during the design and construction of the aeroplane using a mock-up with the same weight and inertia as the actual machine. This first stage lasted 13 months, and took place on an airfield near Paris. Later the actual machine was tested on various airfields and at different seasons of the year.

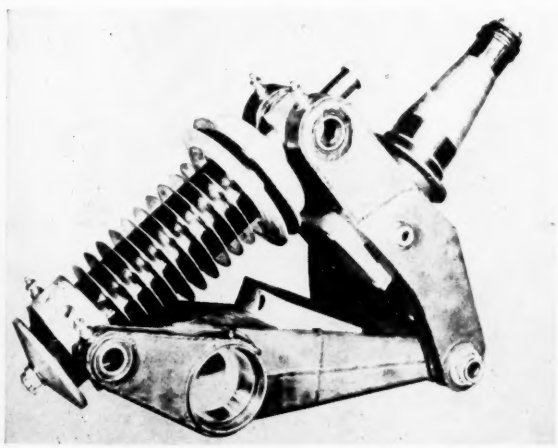


FIGURE 52. The Baroudeur's trolley. Front twin-wheel assembly.

The Baroudeur Trolley

DESCRIPTION

For ground run and take-off, the aeroplane used a trolley fitted with low pressure tyres and similar to an orthodox tricycle undercarriage (Fig. 51).

The structure of the trolley, designed with a view to cheap and rapid production, is mainly made up of beams of welded steel sheet.

Low pressure tyres (2·4 kg./cm.^{2} (34 lb./in.^{2}) for the main rear wheels and 2·9 kg./cm.^{2} (41 lb./in.^{2}) for the front wheels) are fitted to the trolley. The shock absorbers, of very simple design, are rubber compression discs (Fig. 52). The low pressure tyres and the nature of the ground used also contribute towards shock absorption.

The rear beam has a roller (Fig. 53) with the following functions:—

Centring the aeroplane during the hoisting operation.

Housing the driving link of the trolley.

Acting as a hinge for increasing the incidence of the aeroplane.

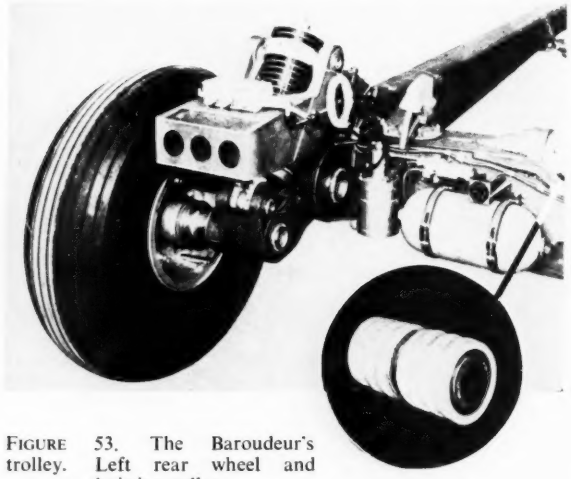


FIGURE 53. The Baroudeur's trolley. Left rear wheel and hoisting roller.

The thrust of the rockets is transmitted from the trolley to the aircraft through a linkage on the front beam. The vertical loads during motion are picked up by an axle on the central beam. A hinged arm at the front of the trolley carries a grooved roller which guides the aircraft when nosing-up for take-off (Fig. 54).

The aeroplane is supported laterally at two points during the ground run and incidence change.

STAGES OF OPERATION

The aeroplane is placed on the trolley, to which it is attached *at one point only*, by an Alkan cable release.

If the runway is long enough the aeroplane takes off under its own thrust in the same way as with an ordinary tricycle undercarriage, but the take-off distance can be reduced by the use of auxiliary rockets.

Stage I

The pilot starts the take-off run with the jet thrust alone. As soon as a suitable speed is reached (this varies with the aircraft weight and rocket power) the pilot fires the rockets. A warning light shows when take-off speed is reached.

The pilot has differential control of the rear wheel brakes of the trolley and thus he can guide the aeroplane-trolley combination during the first stage of the run. At 90 km./h. (56 m.p.h.) the aeroplane controls become effective.

Stage II

When the rockets have finished firing the pilot unlocks the Alkan release (a safety device prevents unlocking while the rockets are alight) and uses the elevator to put the aeroplane into its take-off attitude.

The separation of the plane from the trolley is then automatic as the machine becomes airborne (Fig. 55).

Stage III

The released trolley is subjected to severe wheel and " plough share " braking, initiated by the release of the aircraft.

During trials in 1952 at the Bernes airfield, the trolley, travelling at 185 km./h. (115 m.p.h.) was braked in 70 m. (77 yd.).

For consecutive take-offs (as for formation aircraft) a timing device could be introduced into the " plough share " brake control, so as to fix the stopping point of each trolley, thus eliminating risk of collision.

After it has stopped the trolley is towed away from the take-off area.

Stage IV

The aircraft lands on skids, whose friction is sufficient to ensure rapid braking on stony or dry ground. On grass, the braking power is increased by using retractable claws and, if necessary, by a tail parachute.

Stage V (Fig. 56)

When the aeroplane has landed (with its engine still running) a V.L.R. Delahaye (light reconnaissance truck) brings up the trolley. A cable worked by the V.L.R. winch hoists the aircraft on to it, the Delahaye is uncoupled from the trolley and the aeroplane-trolley

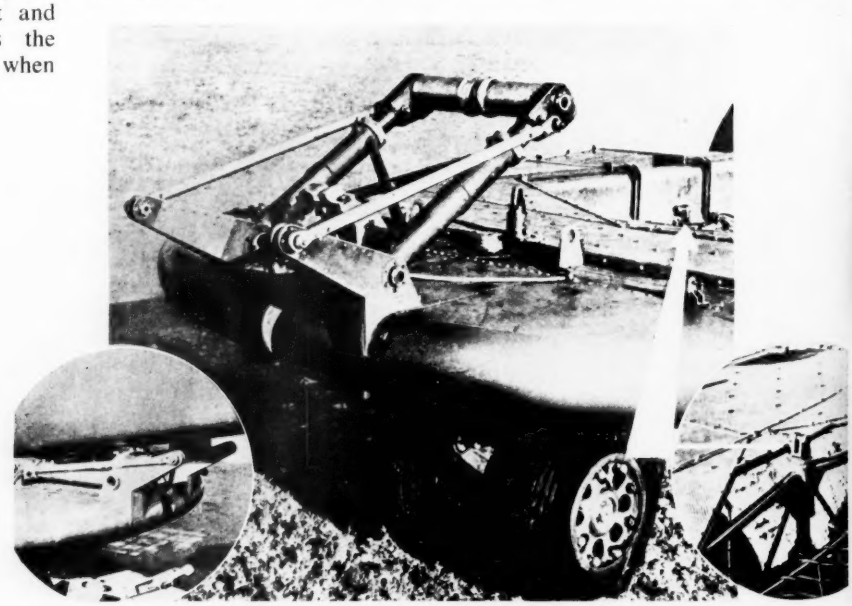


FIGURE 54. The Baroudeur's trolley. General view and details of forward section.

combination leaves the landing area under its own power. This whole operation can be completed in under two minutes.

Except for the short extra time needed for the hoisting operation, the airfield clearance time is the same as for aeroplanes with orthodox undercarriages, but there is the advantage of not being restricted to the taxi-way.

Application of the Skid-Trolley System to Commercial Aircraft

The question of the elimination of the undercarriage for commercial aircraft has often been debated. The advantages claimed are as follows:—

1. Substantial reduction in empty weight, making possible an increase in payload.
2. By using the all-terrain undercarriage it is possible to extend the use of the aeroplane, particularly for freight traffic, to regions where there is insufficient air traffic to justify building modern aerodromes with concrete runways, but where a market could be developed, if the aircraft could use quickly-built airfields. This would contribute to the development of such districts.

FIGURE 55. The Baroudeur just after separation from its trolley.

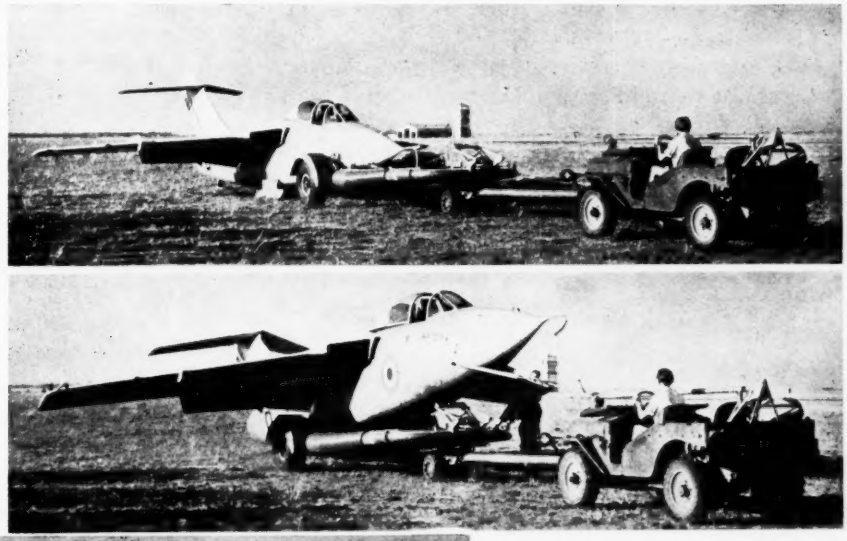
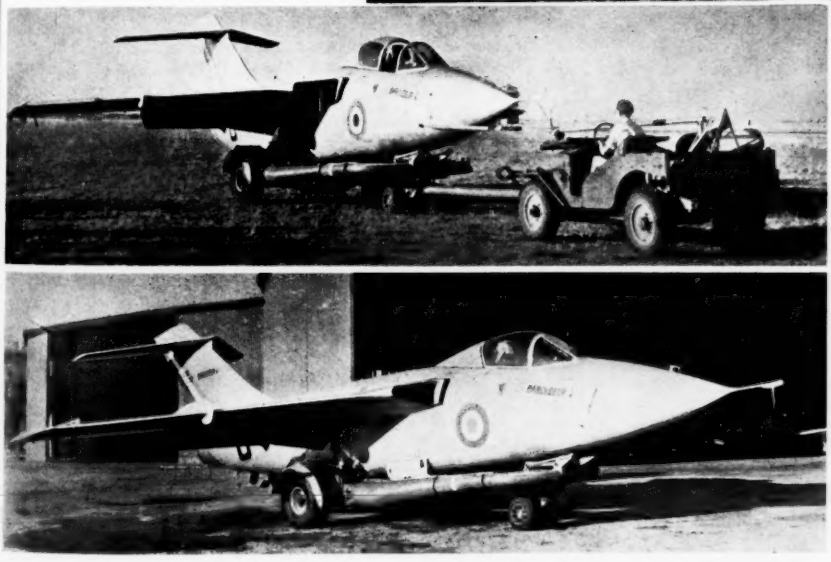


FIGURE 56. Hoisting procedure.



1 (*top*). The trolley is brought under the aircraft which has just landed.

2 (*top*). Aircraft balanced on rear roller after automatic retraction of front skids.

3 (*left*). Aircraft hoisted.

4 (*left*). The aircraft has left the landing area under its own power.

Furthermore, there are other advantages of the use of fixed skids for landing, in place of the present retractable undercarriage: simplification of construction and hydraulic equipment, increased safety, more space available in the aircraft and a reduction in its cost.

Lastly, on aerodromes which already have runways, the aircraft could take off from the runways but could land elsewhere, which would result in an increase of traffic.

In practice, the detailed study of each of these points, in trying to evaluate their advantages, is rather complicated.

Weight

The advantage gained by replacing the present wheeled undercarriage by fixed skids could be evaluated only by comparing the two methods *on the same aircraft*. To obtain the greatest benefit from the fixed-skid solution, it becomes clear on examination that the overall design of the aircraft would have to be modified Thus, a low-wing aircraft with a wheeled undercarriage would have to become a high-wing aeroplane if it were fitted with skids, since the landing flaps determine the ground clearance. In other words, the aeroplane must be designed to suit the new landing chassis. As a result, any comparison of the two solutions on the same aircraft is deceptive. Nevertheless, a theoretical calculation has been made for a few existing transport machines, neglecting these considerations. Calculations show that the undercarriage weight would be reduced by about 40 per cent. of the weight of the wheeled undercarriage and would allow an increase of about 10 to 15 per cent. in payload, a value less than that claimed by other authors.

Landing areas without runways

The transport aircraft used in undeveloped areas do not need the high performance which is the main reason for the use of high pressure tyres. The undercarriage need not be retractable, and the use of concrete runways can therefore be avoided by fitting low pressure tyres.

Take-off from runways of commercial aircraft using trolleys

The weight of the trolley used for this purpose would be an appreciable fraction of the total weight of the aircraft. To avoid increasing the take-off run, auxiliary rockets would have to be used to propel the trolley. This run could be further reduced by increasing the rocket power, but, bearing in mind what was said earlier about the price of rockets, the resulting increase in cost would have to be set against the advantage gained.

The use of a self-propelled trolley is perhaps a more advantageous solution.

Commercial aircraft equipped with skids, landing elsewhere than on runways

In poor visibility, the use of I.L.S. for landing would involve the installation of radio systems so that the glide path and the localiser signals were conveyed to the landing area chosen, which is an additional complication for radio installations.

The foregoing considerations show that it would be bold to claim that the application of the skid-trolley solution to commercial aircraft or even to certain types of these, would produce favourable results. It is only with a radical solution such as that proposed in the United States a few years ago, and mentioned earlier, that the benefits are indisputable. But the realisation of such a project would require research and development which, if applied only to civil aviation, would certainly not obtain the necessary financial backing at present.

BIBLIOGRAPHY

1. PRITCHARD, J. LAURENCE. The Wright Brothers—A Survey and Tribute. *Journal of the Royal Aeronautical Society*, December 1953.
2. LECARME, J. Avions sans trains—Avions sans bases. *Inter Avia* No. 5, 1951.
3. ARPURT, LT.-COLONEL. Terrains et Pistes d'Opérations. *Forces Aériennes Françaises*, June 1952.
4. ARPURT, LT.-COLONEL. Pour raccourcir les Pistes. *Forces Aériennes Françaises*, July 1952.
5. ELDRED, W. Landing Gear Design as Applied to Modern Aircraft. Preprint S.A.E. No. 146.
6. Le raccourcissement des pistes (Reducing the Size of Take-off and Landing Bases). *Inter Avia* No. 7, 1954.
7. HANDLEY PAGE, SIR FREDERICK. Vers un avion plus sûr et une infrastructure moins chère. *Technique et Science Aéronautiques* No. 3, 1950.
8. RENOLLAUD, J. Faut-il supprimer les trains d'atterrissage? *Technique et Science Aéronautiques* No. 4, 1951.
9. LUCIEN, R. Evolution des atterrisseurs des avions modernes. *Technique et Science Aéonautiques* No. 5, 1948.
10. ARPURT, LT.-COLONEL. Considérations sur les Aérodromes. *Forces Aériennes Françaises*, January 1955.
11. MONTGOMERY, FIELD MARSHAL. Regard par le fenêtre sur la troisième guerre mondiale. *Nouvelle de l'OTAN*, Tome 2, No. 10, 1st November 1954.
12. L'Aérodrome de Brienne-le-Château. *La Technique Moderne Construction*, Tome IX, No. 6, June 1954.
13. U.S.A.F. Air Bases in Europe. *The Aeroplane*, 12th February 1954.
14. Rapport de M. Pellenc. Doc. C.R. No. 46.
15. Heathrow Aerodrome. *The Aeroplane*, 9th July 1954.
16. BRYAN, L. A. Cost and Planning. *Air Affairs*, December 1950.
17. BOUCHÉ, H. Comment agir sur le bilan humain de l'Aviation Civile. Bulletin I.C.A.O., September 1954.
18. TOMLINSON, M. J. The Design and Construction of Airfield Pavements. *Journal of the Royal Aeronautical Society*, December 1952.
19. Que pensez-vous de l'Infrastructure? *Forces Aériennes Françaises*, November 1950.
20. Operation Wittles. *Aviation Operation*, April 1949.
21. La Piste K.6. *Military Review*, July 1954.
22. MIKSCHE, LT.-COLONEL. Les causes de la défaite allemande. *Forces Aériennes Françaises*, June 1951.
23. La puissance aérienne de l'OTAN—Les Bases (NATO'S Aerial Punching Power). *Inter Avia* No. 8, 1954.
24. GUDERIAN, GENERAL H. Les trains d'atterrissage à chenilles (Track Undercarriages for Aircraft). *Inter Avia* No. 8, 1954.

25. Effets d'une bombe atomique sur les aérodromes modernes. *Forces Aériennes Françaises*, October 1953.
26. Aérodromes. I.C.A.O., Annexe 14 .
27. ARPURT, LT.-COLONEL. Considérations sur les Aérodromes. *Forces Aériennes Françaises*, January 1955.

CATAPULTS.

28. BARJOT, VICE-ADMIRAL. Le porte-avions d'aujourd'hui et de demain (The Present and Future of the Aircraft Carrier). *Inter Avia* No. 3, 1953.
29. BODDINGTON, L. Naval Aircraft and Carrier Equipment. *Journal of the Royal Aeronautical Society*, October 1947.
30. Lancement des avions par catapulte. Génie Civil, 1st September 1947.
31. Steam Launch. *Flight*, 25th January 1952.
32. Navy Steam Launch. *Flight*, 21st January 1955.
33. Navy Plans Converting Carriers to Steam Catapult. *Aviation Week*, 23rd August 1954.
34. Dispositif de lancement du navire escale "Westfalen." V.D.I., 2nd June 1934.
35. La Ligne de l'Amérique du Sud. *Luftwissen*, August 1934.
36. Castaing—Catapulte fixe Penhoet installée sur l'Ile de France. *L'Aéronautique*, November 1928.
37. CAGNOTTE, L. Lancement des hydravions par catapulte. Travaux du IVe Congrès International de Navigation Aérienne.
38. COURTNEY, F. T. Le lancement des hydravions à partir du sol (Land Launched Seaplanes). *Aviation*, September 1936.
39. Katapulte und Katapultieren von Flugzeugen. Notice Heinkel.
40. Catapulte de Campagne Junkers pour Avion de Combat à Pulso-réacteur EF.126 Document S.D.I.T. Ref. 10.155/2R 1.
41. JOYNER, U. T. and HORNE, W. B. Considerations on a Large Hydraulic Jet Catapult. N.A.C.A. T.N. 3203, 1951.
42. L'Electro Pult. *Aviation*, October 1947.
43. Documentation de la Sté Latécoère.
44. RODERT, LEWIS, A. Idea to Aid Landing and Take-off. *S.A.E. Journal*, March 1947.

L'ARBALÈTE.

45. FIEUX, J. Le Problème du Freinage et du Catapultage des Avions. *Revue Arts et Métiers* No. 5, May-June 1952.
46. ARPURT, LT.-COLONEL. Pour Raccourcir les Pistes. *Forces Aériennes Françaises*, July 1952.
47. L'Arbalète. Application au NC.856A. Bulletin S.N.C.A.N. No. 2, November 1954.
48. L'Arbalète. *Les Ailes*, 23rd October 1954 and 6th November 1954.
49. Documentation Sté Nationale de Constructions Aéronautiques du Nord.

METAL TRACK.

50. COR, J. L'Infrastructure de 1932 à 1947. Quinze ans d'Aéronautique Française—Union Syndicale des Industries Aéronautiques.
51. GRIGSON, REGINALD RONALD WEST. Metal Track Surfacing. *The Civil Engineer in War*, Vol. I, Airfields, Road, Railways and Bridges. 1948.

RAMP LAUNCHING.

52. GATLAND, K. *Development of the Guided Missile*. Iliffe & Sons Ltd., 1954.
53. L'engin Regulus. *Aviation Week*, 8th February 1954.
54. The Martin "Matador." *Flight*, 9th July 1954.
55. The Martin "Matador." *Aero Digest*, December 1954.
56. The Natter Jet Interceptor. *Aircraft of the Fighting Powers*, Vol. VII. The Harborough Publishing Co., 1946.
57. The Natter Jet Interceptor. *Inter Avia*, 1st August 1954.

CARRIAGES ON LANDING TRACKS.

58. Trials at Holloman. *Flying Safety*, September 1954.
59. Les troies voies ferrées de l'Air Force (The Three Test Tracks Operated by the Holloman Air Development Center and the Air Force Flight Test Center. *Aviation Week*, 7th September 1953.
60. Le traineau N.A.A. d'Edwards (High Speed Test Sled built at Edwards by N.A.A.). *Aviation Week*, 13th April 1953.
61. Le projet Snort. *Aviation Age*, August 1952.
62. Rail Launchings at Muroc. *Journal of American Rocket Society*, June 1948.
63. One-man Open Sleigh—Lt.-Colonel Stapp. *Flight*, 7th January 1955.

TAKE-OFF AND LANDING ON CABLES.

64. Colin—Parmi les précurseurs du Ciel—Blériot.
65. MORTANE, J. Louis Blériot.
66. LECARME, J. Avion sans train—Avion sans bases. *Inter Avia* No. 5, 1951.
67. The Brodie System. *Flying*, December 1945.
68. Atterrissage sur câble. *Aéro Revue*, July 1946.
69. Dispositifs oléo-pneumatiques. Dossier Décollage "Vampire Mk. 53 sur skis."
70. Brevet No. 1044 99, 9th November 1951. Procédés et dispositifs pour permettre le décollage sur tous terrains d'aéronefs munis de skis d'atterrissage. Société "Les Dispositifs Oléo-Pneumatiques."

GROUND BRAKING AND BELLY-LANDING DEVICES.

71. HAWTHORNE, RANDOLPH. Bringing the Aircraft to a Stop. *Aviation Age*. October 1954.
72. Brevet U.S. 2.675.197, 13th April 1954, Crash Barrier. *Aviation Age*, p. 72, October 1954.
73. Crash Barrier. *Aviation Week*, 15th June 1953.
74. MACMILLAN, NORMAN. What can the Flexible Deck do for Naval Aircraft? *Aircraft*, August 1950.

LOW PRESSURE TYRES.

75. CASSIE, W. FISHER. The Influence of Tyre Pressure on the Design of Aerodrome Pavements. *Journal of the Royal Aeronautical Society*, September 1952.
76. Caractéristiques des pneus et roues d'un avion typique. Document S.N.C.A.S.E., Cote Dd. 368.

CATERPILLAR TRACK GEAR.

77. MACLAREN, O. F. Caterpillar Tracks. *Aeronautics*, June 1949.
78. GUDÉRIAN, GÉNÉRAL. Les trains d'atterrissage à chenilles (Track Undercarriages for Aircraft). *Inter Avia* No. 8, 1954.
79. Essais de chenilles sur Fieseler. Document S.D.I.T. 12250/2R1.
80. Atterrisseur Vinay. *L'Aérophile*, November 1927.
81. Atterrisseur Bonmartini. Notice de l'Etablissement Sciences et Techniques—Edizione Ridotta.
82. ELDRED, W. Les trains d'atterissage des avions modernes. Preprint S.A.E. No. 146.
83. MCSURELY, ALEXANDER. New C82 Installation Developed by Fairchild and Firestone. *Aviation Week*, 5th July 1948.
84. The Track Landing Gear System. *Plane Facts*, May 1948.
85. SCHOENEN, HERMANN. The Caterpillar Takes to the Air. *Aero Digest*, January 1950.
86. Expérimentation du train à chenilles Bonmartini sur Piper L.18. *Inter Avia* No. 3143, 22nd January 1955.

SKIDS AND SKIS.

87. BRUCE, J. M. The Sopwith Pup. *Flight*, 1st January 1954.
88. Aluminium Aircraft Skis. *Modern Metals*, May 1947.
89. SYDOW, J. Essais sur Skis—Pression sur le sol. *Deutsche Luftfahrtforschung* 2 WB/UM/667, April 1942.
90. BURSH, ARTHUR A. Skis Broaden Aircraft Utility. *Aero Digest*, September 1947.
91. The D.H. C2 "Beaver." Catalogue De Havilland, Canada.

92. KLEIN, GEORGE J. The Snow Characteristics of Aircraft Skis. National Research Council (Canada) NRC MM 57, April 1946.
93. MEYER, JOHN H. MacDonnell XF 85 Landing Skis Development. *Aero Digest*, December 1949.
94. KLEIN, GEORGE J. Aircraft Skis Research in Canada.
95. Vampire with Skids. *Aviation Week*, 25th April 1949.
96. NORTHROP, JOHN K. Development of All-Wing Aircraft. *Journal of the Royal Aeronautical Society*, June 1947.
97. PORT, W. G. A. Essais en vol du Messerschmitt Me 163B. R.A.E. Report 2255.
98. GALLOIS, LT.-COLONEL. L'Occident s'est-il donné les armes de sa stratégie (Is Western Air Power Adequate?) *Inter Avia*, December 1950.
99. Les Hydravions intercepteurs (Water Based Interceptors). *Inter Avia* No. 8, 1954.
100. Les Hydroskis (Hydro-Skis). *Shell Aviation News* No. 175.
101. Aircraft with Skids. *R.A.F. Review*, November 1952 and August 1953.
102. More About the Jindivik. *The Aeroplane*, 19th June 1953.
103. MAGUIRE, D. R. Enemy Jet History. *Journal of the Royal Aeronautical Society*, January 1948.

COMBINED WHEELS AND SKIS.

104. GAMBU, J. Quand le Mistral fait du ski sur l'herbe. *Aviation*, 3rd March 1955.

THE MULTI-TERRAIN UNDERCARRIAGE.

105. NORTHROP, JOHN K. Development of All-Wing Aircraft —The Northrop XP79. *Journal of the Royal Aeronautical Society*, June 1947.
106. PORT, W. G. A. Messerschmitt Me 163B. R.A.E. Report Aero No. 2255.
107. MAGUIRE, D. R. Enemy Jet History. *Journal of the Royal Aeronautical Society*, January 1948.
108. The Beaver. De Havilland, Canada.

APPENDIX

(*a*) *Cost of building a N.A.T.O. base*

	Francs	£
Runways	540 m.	540,000
Taxi-ways	270 m.	270,000
Connecting roads	55 m.	55,000
Dispersal points	60 m.	60,000
Approaches and over-runs ...	275 m.	275,000
	1,200 m.	1,200,000
Cost of land Expropriations Lighting—ground work—radio—buildings	1,400 m.	1,400,000
Total	2,600 m.	2,600,000

(Ref: Note by Lt.-Col. Arpurt, Document AN 8023—Monteil Report)

(*b*) *Civil airports*

1. COST OF THE GRAND ORLY EXPANSION SCHEME FOR THE PERIOD 1950-1954

	Francs	£
Construction of the 2,400 m. (2,600 yd.) N.S. runway and extension of other runways and perimeter roads	3,600 m.	3,600,000
Hangars and workshops ...	1,500 m.	1,500,000
Passenger buildings ...	500 m.	500,000
Technical staff buildings ...	350 m.	350,000
General installations (telephone, communications, etc.)	1,700 m.	1,700,000
Expropriations	450 m.	450,000
Total	8,100 m.	8,100,000

The estimated total cost of the expansion programme, to be completed by 1958, is £30 m. Of this overall sum the expropriations amount to £3½ m.

(Ref: Morice Report—Document AN 9389. Note on Orly Airport.)

2. COST OF EXPANDING NICE AIRPORT

	Francs	£
Runways and perimeter roads	900 m.	900,000
Buildings	950 m.	950,000
Cost of land and expropriations	1,400 m.	1,400,000
Communications	750 m.	750,000
Total	4,000 m.	4,000,000

3. COST OF DEVELOPING THE MAISON BLANCHE AIRPORT, ALGIERS

	Francs	£
Total cost	5,000 m.	5,000,000
— of which the runways and perimeter track cost	1,300 m.	1,300,000

(Ref: Parisien Libéré, 29th October 1954)

4. COST OF UPKEEP OF AERODROMES

To the initial cost of construction must be added the annual upkeep, although this is relatively small.

At Schiphol, Amsterdam, the average annual upkeep for the years 1949-50-51 was £33,000, or 1·6 per cent. of the capital cost. As regards N.A.T.O. aerodromes, experts have made a firm estimate of one per cent. of the capital cost, or about £26,000. Moderate as this figure is, it is obvious that the upkeep of grass airfields would be considerably less.

(Ref: " L'Aéroport de Paris " by C. Postel. Note by Lt.-Col. Arpurt.)

(*c*) *Loss of striking power due to airfield costs*

It is interesting to estimate roughly the number of squadrons which could have been equipped if the money spent on building the 160 N.A.T.O. runways in Western Europe had been used for the purchase of aircraft.

$$160 \times £1{\cdot}2 \text{ m.} = £192 \text{ m.}$$

Taking £100,000 as the cost of a fighter bomber:—

$$\frac{192{,}000{,}000}{100{,}000} = 1{,}920 \text{ aeroplanes, or about 80 squadrons.}$$

The most optimistic estimates of the striking power of the air forces in the Central European sector, are about 2,500 aircraft. Thus, for the same cost, it would have been possible to reinforce considerably the air power in this sector.

(*d*) *The need for concrete runways*

A—INCREASE OF TYRE PRESSURE

1. *Military aircraft*

	Year	All-up weight		Tyre pressure	
		kg.	lb.	kg./cm.²	lb./in.²
Dewoitine 520	1938	2,780	6,140	3·6	51
North American F-51D	1942	5,897	13,000	4·0	57
Lockheed F-80C	1945	9,072	20,000	10·0	142
Republic F-84 E	1949	9,980	22,000	9·5	135
North American F-86	1950	7,500	16,500	11·0	156
Boeing B-17G	1941	30,844	68,100	6·0	85
Boeing B-47C	1950	81,647	180,000	12·5	178
Republic F-84F	1953	12,200	26,900	18·2	258
Dassault Mystère IVA	1953	7,400	16,300	14·0	200

2. *Civil aircraft*

	Year	All-up weight		Tyre pressure	
		kg.	lb.	kg./cm.²	lb./in.²
Douglas DC-3	1936	11,850	26,100	3·7	53
Dewoitine 338	1936	11,100	24,500	4·0	57
SE-161 Languedoc	1940	23,300	51,400	4·2	60
Douglas DC-4	1942	33,110	73,000	6·3	90
Lockheed Constellation 749A	1945	48,535	107,000	8·4	120
Bristol 170	1946	20,000	44,000	4·6	65
Boeing Stratocruiser	1948	64,650	142,500	8·4	120
SE-2010	1949	77,500	171,000	6·0	85
D.H. Comet	1952	48,725	107,500	8·4	120
Douglas DC-6B	1953	48,125	106,000	7·7	110

B—INCREASE IN TAKE-OFF DISTANCE

1. *Military aircraft*

	Wing loading		Length of ground run	
	kg./m.²	lb./ft.²	metres	yd.
Dewoitine 520	174·5	36	218	238
North American F-51D	272	56	830	910
Lockheed F-80C	412	85	1,850	2,020
Republic F-84E	413	85	2,150	2,350
Boeing B-17G	234	48	1,150	1,260
Boeing B-47C	516	106	2,860	3,130

2. *Civil aircraft*

	Ground run		Accelerate-stop distance	
	metres	yd.	metres	yd.
Dewoitine 338	305	335	—	—
Douglas DC-3	300	330	1,200	1,310
Douglas DC-4	1,130	1,240	1,520	1,660
SE-161 Languedoc	700	770	1,400	1,530
Lockheed Constellation	600	660	1,500	1,640
Bristol 170	440	480	1,050	1,150
Douglas DC-6B	1,310	1,430	1,935	2,120
Boeing Stratocruiser	1,150	1,260	1,900	2,080
SE-2010	1,340	1,470	2,070	2,270
D.H. Comet	1,750	1,920	2,200	2,410
Douglas DC-7	1,020	1,120	1,945	2,130

(*e*) *Comparison of I.C.A.N. and I.C.A.O. Regulations*

Take-off conditions

I.C.A.N.

The aeroplane must clear a height of 20 m. (66 ft.) at a distance of 600 m. (660 yd.) from the start of a normal take-off at sea level.

I.C.A.O.

Annexes 6 and 8

The accelerate-stop distance, the distance required to attain a height of 15 m. (50 ft.) above the take-off area, with the critical engine becoming inoperative at the critical point, shall not exceed the length of the take-off area.

The accelerate-stop distance is the distance required to reach the Power Failure Point and, assuming the critical engine to fail at this point, to bring the aeroplane to a stop.

AIR COMMODORE F. R. BANKS, C.B., O.B.E., *Fellow*, proposing a vote of thanks to the Lecturer:

He was very pleased and honoured to be asked to propose this vote of thanks because he had a great affection for France and also for Blériot; for Blériot seemed attached to him or he seemed to have been attached to Blériot throughout his life. When very young, he believed he first met Blériot in 1909. Then, he remembered going to see the great man's aeroplane when he landed from his Channel flight. Many years afterwards, he was honoured by A.F.I.T.A. in being asked to give the First Louis Blériot Lecture.

While there was no question of the credit due to the Wright Brothers for the first flights in powered aircraft, there was also no question that to the French and France should go the credit of the start of the aviation era, in 1909; and there had been many ingenious aeroplanes and engines built by their French friends—the famous Gnôme engine was an outstanding example of the first practical low weight power unit; and the Antoinette engine, although less successful, was full of ideas ahead of its time, *i.e.* fuel injection and evaporative cooling.

What struck him now today (and he had been privileged to go to France quite a lot and visit their establishments and factories) was that there had been a definite renaissance in French aviation since the War, and French ingenuity was well shown by the things they had heard and seen in the lecture. He had seen the Baroudeur and thought it was one of the most ingeniously conceived aircraft built in recent years. He used to say that the French did not understand the word "development"—and they had no word for it in their dictionary—but he must now alter that by admitting that the development done on the Baroudeur, with its trolley launching and its landing equipment, to ensure ground stability and operational feasibility, was one of the outstanding post-war developments in any country.

He was not going to comment on the paper, except to call it a masterly effort. Monseur Hereil had given much data of great value to the aircraft designers of the world, and he thought the lecture would prove to be a classic on its subject.

There was one small point in the lecture which needed amplification—the Boeing and Fairchild caterpillars were designed by George Dowty; but, since it was a war-time development, security reasons had prevented the originator's name from being given.

In all aids and alternatives to the runway, it was a matter of time and timing; and whether the technique of developing them, and the aircraft to make full use of them, could be brought to practical account in a reasonable period.

The Baroudeur probably made its own concrete because it burned up enough of the grass and heated up the earth to make it pretty hard! He thought that civil aircraft would have to have the conventional runway for a long time; but they were getting to the limit of runway length and, therefore, it was up to the aircraft designers to get aeroplanes up and down in reasonable limits—but even jet aircraft such as the Comet and the Boeing 707 had been designed to use the normal runway. For military aircraft it was another matter and he thought that various launching methods, including vertical take-off, would come.

He thanked Monsieur Hereil again for giving them such an excellent paper, and for the way he had written and presented it.

MR. B. S. SHENSTONE, A.F.I.A.S., A.F.C.A.I., *Fellow*: He was deeply impressed by the paper that had just been presented. Two points he thought were most remarkable. One was that, after saying that he would not talk about any of the things that they thought he would talk about, the lecturer then was able to interest them by a remarkable list of inventions and gadgets, some of which they had never heard about. The other point he would like to make was that, although Monsieur Hereil said and made a very great point of doing away with runways, he did not do away with fields. In fact he thought he particularly went in for ploughed fields! However, he took great pleasure in seconding this vote of thanks and felt that they all ought to be very grateful for having heard this great lecture.

SIR SYDNEY CAMM: That concluded the proceedings, but he would like to mention one point that had been in his mind throughout the lecture and that was how much they owed to the pneumatic tyre. He thought it was 21 years ago that the specification of the Hurricane was issued from the Air Ministry, and this specified a maximum tyre pressure of 35 lb./in.^{2}. As they knew, today they were using tyre pressures of around 200 lb./in.^{2}. It was interesting to speculate what they would have done with no pneumatic tyre. Probably some of the mechanical launching arrangements which they had heard described that evening would have been in use today.

Following the Lecture a Dinner was given by the Council of the Society at 4 Hamilton Place, W.1, at which the following were present:—

Mr. J. E. Adams, London Manager, Air France; Monsieur L. S. Armandias, Correspondent in Great Britain to the Association Française des Ingénieurs et Techniciens de l'Aéronautique.

Dr. A. M. Ballantyne, T.D., A.F.I.A.S., A.F.R.Ae.S., Secretary of the Royal Aeronautical Society; Air Commodore F. R. Banks, C.B., O.B.E., M.I.Mech.E., F.Inst.Pet., F.R.Ae.S., Member of Council of the Royal Aeronautical Society, Louis Blériot Lecturer—1948; Captain K. J. G. Bartlett, C.B.E., M.Inst.T., M.S.A.E., A.F.R.Ae.S., President of the Fédération Aéronautique Internationale; Mr. E. C. Bowyer, C.B.E., Director of the Society of British Aircraft Constructors; The Rt. Hon. J. Boyd-Carpenter, M.P., Minister of Transport and Civil Aviation; Sir John S. Buchanan, C.B.E., A.M.I.Mech.E., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Member of Council and Honorary Treasurer of the Royal Aeronautical Society.

Sir Sydney Camm, C.B.E., F.R.Ae.S., President of the Royal Aeronautical Society; Mr. M. L. Clarke, Sabena (Belgian Air Lines); Professor A. R. Collar, M.A., D.Sc., A.F.I.A.S., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Sir Harold Roxbee Cox, Ph.D., D.I.C., B.Sc., M.I.Mech.E., F.I.A.S., F.R.Ae.S., Past President of the Royal Aeronautical Society.

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Monsieur G. de Faget, Le Chef du Service des Relations Extérieures et de la Documentation l'Office National d'Études et de Recherches Aéronautiques.

Mr. H. R. Gillman, O.B.E., A.F.R.Ae.S., Director-General of the Fédération Aéronautique Internationale.

Mr. Raoul Hafner, F.R.Ae.S., Chief Designer, Helicopter Department, Bristol Aeroplane Co. Ltd., Louis Blériot Lecturer—1954; Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Mr. P. A. Hearne, D.C.Ae., D.L.C., Grad.R.Ae.S., Member of Council of the Royal Aeronautical Society; Monsieur Georges Hereil, Louis Blériot Lecturer—1955.

Monsieur J. Jarry, Président, Association Française des Ingénieurs et Techniciens de l'Aéronautique; Mr. E. T. Jones, C.B.E., O.B.E., M.Eng., F.R.Ae.S., Member of Council of the Royal Aeronautical Society.

Mr. H. Knowler, A.M.I.C.E., F.R.Ae.S., Technical Director of Saunders-Roe Ltd., Louis Blériot Lecturer—1952.

The Rt. Hon. Selwyn Lloyd, C.B.E., T.D. Q.C., M.P., Minister of Supply.

Mr. P. G. Masefield, M.A., M.Inst.T., F.I.A.S., F.R.Ae.S., Vice-President of the Royal Aeronautical Society; Monsieur H. Melville, Assistant to M. Georges Hereil.

Sir Frederick Handley Page, C.B.E., F.C.G.I., Hon.M.Inst.T., Hon.F.I.A.S., Hon.F.R.Ae.S., Louis Blériot Lecturer—1950; Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General of the Royal Aero Club; Monsieur le Colonel A. Puget, D.S.O., Air Attaché to the French Embassy.

Mr. N. E. Rowe, C.B.E., D.I.C., B.Sc., A.C.G.I., M.Inst.T., M.I.Mech.E., F.I.A.S., F.R.Ae.S., President-elect of the Royal Aeronautical Society; Monsieur Professeur Maurice Roy, F.R.Ae.S., Le Directeur, Office National d'Études et de Recherches Aéronautiques, Louis Blériot Lecturer—1951.

Mr. B. S. Shenstone, M.A.Sc., A.F.I.A.S., F.R.Ae.S., Member of Council of the Royal Aeronautical Society.

Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Royal Aeronautical Society.

Structural Safety

by

A. G. PUGSLEY, O.B.E., D.Sc., F.R.S., F.R.Ae.S.
(Professor of Civil Engineering, University of Bristol)

The 943rd Lecture to be given before the Royal Aeronautical Society was the 19th Main Lecture to be held at a Branch and was given before the Preston Branch on 10th March 1955. Mr. D. L. ELLIS, F.R.Ae.S., Chairman of the Branch, introduced Mr. N. E. ROWE, C.B.E., A.C.G.I., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., President-Elect of the Society, who presided.

MR. D. L. ELLIS: This was a very important occasion for the Preston Branch because it was the first time that a Main Society Lecture had been held on their "ground." His brief and pleasant duty was to introduce Mr. N. E. Rowe, who would take the Chair. Mr. Rowe was Vice-President and President-Elect of the Society, and the Branches in particular owed a great debt to him as he had been active for many years in fostering their interests.

MR. N. E. ROWE: His main purpose was to introduce the Lecturer, but before doing so he had to convey an apology from the President, Sir Sydney Camm, who had found that the pressure of business generally had prevented him from getting there. Sir Sydney was deeply sorry because he realised the tremendous work that was done for the Society as a whole by the Branches and the part the President in particular played on occasions of this sort when, as it were, the Main Society came out to the Branch.

It gave him great pleasure to be Chairman of this first Main Society Lecture at the Preston Branch and to see such a splendid gathering. There were representatives of a number of Branches, Manchester, Luton, Chester, Glasgow, Brough (that was himself) and he was told that there were two Honorary Members of Branches, one Halton, the Secretary of the Society, and the other Hatfield, Mr. D. C. Smith and he also happened to be an Honorary Member of that Branch himself so that he thought that they were very well represented.

The Lecturer hardly needed any introduction. He had been eminent in aeronautics almost ever since he could remember. He had become even more eminent in structures in recent years, carrying on his work as Professor of Civil Engineering at Bristol, where he was now. He began his career in aeronautics on airship design, working on the R.101, which he supposed for a structural engineer could not be better. He continued in the very new province of aeroelastics, commonly known as "flutter" in those days, to which he made an outstanding contribution. Professor Pugsley was now unique in the combination of his aeronautical knowledge and his structural position in this country and it was a great privilege, and honour to the Branch and to the Society that he had come to lecture to them on the subject of safety in structures. Among his other attainments, Professor Pugsley held the important position of Chairman of the Aeronautical Research Council, so that he really was at the head of affairs in research in aeronautics in this country.

1. Introduction

The present preoccupation of aircraft designers and users with fatigue problems, brought to a head by the Comet disasters, has rendered the notion of the finite life of an aeroplane a commonplace to the man in the street, and has made the assessment of probabilities of failure and the collection of statistics regarding loads and structural properties a matter of detailed concern for all designers. This was not always so. In 1939, when Fairthorne and I essayed a first paper on airworthiness statistics[1] it received practically no attention and publication was delayed for years until after the 1939-45 War. Even in 1942, an exploratory "Philosophy of Aeroplane Strength"[2] brought smiles to the faces of practical designers rather than the real interest that the "new slant," as some said, of its probability approach raised in a few scientists.

A great change of climate surrounding the use in airworthiness matters of statistical and probability concepts has occurred during and since the war. Walker can now discuss the estimation of the life of an aircraft[3] without raising any other thought than the practical seriousness of the matter in hand; and this practical interest is by no means confined either to this country or, indeed, to aeronautics itself. When in 1951 I read a paper to the Institution of Civil Engineers on "Concepts of Safety in Structural Engineering"[4], I found that the response from abroad was at least as advanced as any from this country. Marcel Prot of France[5], two years before, and A. I. Johnson of Sweden[6], in 1953, have both worked out the economy of structural design in terms of risk of failure; more broadly, Freudenthal, now of U.S.A., has developed the relevant probability theory and advanced and widened its applications, notably in papers published by the American Society of Civil Engineers in 1947 and 1954[7, 8]. As a result, civil engineers in the western world are almost as accustomed to discuss safety in terms of probability and related concepts as are aeronautical engineers.

A committee of the Institution of Structural Engineers, working with this background, has just published its first report[21] on structural safety, a main aim of which is to provide a philosophical framework within which the safety clauses of standard codes of practice can in future be set.

In these much altered circumstances, I am here going to assume that the general concepts of safety contained in this literature are, if not wholly accepted, at least commonly known and used as a basis for

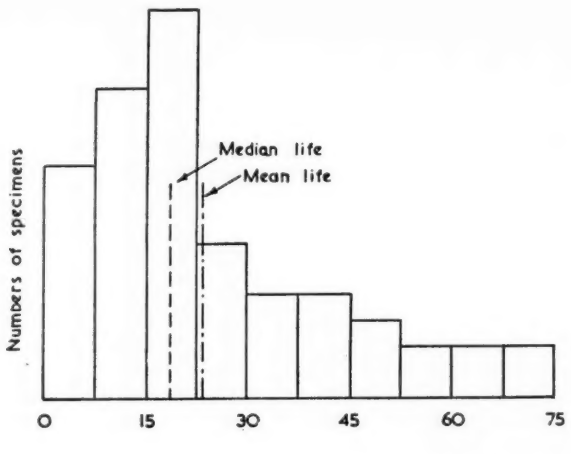

FIGURE 1. Frequency histogram for fatigue test results on 75 S-T aluminium.

discussion. By so doing, attention can be concentrated upon certain new, or currently important, aspects of structural safety in the light of what has gone before.

2. Fatigue

Structural fatigue presents outstanding safety questions at the present time. This is not the place to attempt to discuss these questions broadly or comprehensively, but I would like to comment on some aspects of the matter.

In the first place, the estimation of a safe life depends, among other things, on the scatter of fatigue test results, and on this there are singularly few adequate experimental results. In 1947, the only readily available tests that were at all comprehensive were some on welded joints, which I quoted at the time[9]. Now there is a new and more fundamental attack led by Freudenthal and Gumbel in their recent paper to the Royal Society[10]. As an example, they set out the results for a series of rotating beam tests on 75 S-T aluminium alloy. At a stress level of $\pm 45{,}000$ lb./in.^{2}, 17 specimens give fatigue lives ranging from 63,000 to 463,000 cycles with a mean of 214,000, whereas at a stress of $\pm 30{,}000$ lb./in.^{2}, nearing the conventional endurance limit, tests on 57 specimens give lives ranging from 430,000 cycles to 117,423,000 cycles with a mean of 23,324,000; such results underline the magnitude of the problem, even though the scatters involved may not be typical of complex structures. If the second set of these results is plotted to show the frequency distribution of the measured lives, we have the curve of Fig. 1 and at once notice its adversely unsymmetrical nature. The curve gives a "most probable" or median life of 19,117,000 cycles as compared with the mean of 23,324,000 cycles. The standard deviation is 20,038,000 cycles and so approximates to the mean itself. Fortunately, the same results, plotted as a frequency curve against life in cycles on a log scale, approximate to a normal or Gaussian distribution, a mathematically convenient fact that the work of Freudenthal and others has shown to be fairly general. This permits not only of the better planning and interpretation of fatigue tests, but also gives hope for the estimation of fatigue life with greater reliability. The possibility of a large and unsymmetrical scatter of test results in the region of most interest for the estimation of the safe life of an aeroplane, nevertheless emphasises the importance of comprehensive fatigue tests on some typical vital parts of aeroplane structures.

A second point relates to the variation of loading on structures, the cumulative "law," and appropriate schemes for testing. In the recent past, English engineers have used Miner's cumulative law as a means of determining the most significant constituent, in amplitude and frequency of occurrence, in the measured records of flight loads; and they have been comforted in the deduction in this way of a "most damaging cycle" from the fatigue standpoint by a number of indirect pointers to the reasonableness of the result. But in France, and now in America, Prot[11] and Freudenthal[12] have sought to deduce from the load records a test cycle programme more representative of the actual random loading. In aeronautical terms, Prot's scheme is to analyse a flight load-time record by a diagram showing the frequency of the occurrence of a given level of load and thence to represent the actual random record by a regularised "stepped" programme of cycles, each of fixed load amplitude, for given periods of time. This process is illustrated by the diagrams of Fig. 2. Such a procedure no doubt introduces the well-known "overstressing" and "under-stressing" effects present in the real cycle, but leads, of course, to a more complex testing programme. It would seem well worth while trying out the effects of these more realistic programmes compared with those of the corresponding cumulative law programme It might be found that a simple combination of both approaches—as, for example, the use of the cumulative law cycle with the insertion, at appropriate intervals, of a few cycles of large amplitude loads, if appropriate, alternating in sign—would prove a reasonable compromise.

Both the above points relate to matters that have already received considerable attention, but my third point, the effects of corrosive influences, seems in relation to the modern problem to have been largely overlooked. In the nineteen-twenties, with the extended

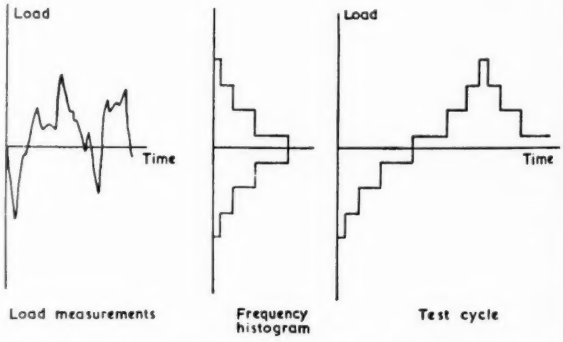

FIGURE 2. Representation of random load history by incrementally varied load cycle.

adoption of steel and then aluminium alloys in airframes, the influence of corrosive conditions on fatigue received considerable attention. Some of this work seems to me relevant today and I would like to draw attention to its major features.

Gough and Sopwith in this country, and McAdam in America, were responsible for much of the work. Most of us will recall that the fatigue endurance limits of metals can be very severely reduced by the presence of salt water or salt spray during the fatigue period. In such circumstances the endurance limits of steels are often reduced to a third of their value in air, and of aluminium alloys to perhaps one half. What is not so commonly appreciated nowadays is that fatigue tests in fresh water show quite large reductions also. Fig. 3 shows the results of some tests by McAdam[13] on a tempered duralumin. The curves show the large effect of fresh water conditions, particularly when large numbers of cycles are concerned. They also show how, under corrosive conditions, the increased slope of the *S-n* curve makes unreal any suggestion—and this applies also to steels—of a definite endurance limit.

Another feature of corrosion-fatigue results is that, in nearly all cases, the conventional endurance limits are much more a function of chemical composition than of static strength attained by cold working or heat treatment. Thus for 10^7 cycles, the fatigue limit for the duralumin of Fig. 3, whether tempered or annealed, was much the same, although at 10^4 cycles the former was markedly the better. This is a further handicap to the use of many modern alloys under fatigue conditions, for even in air, as is well known, their endurance limits lag behind their static strength properties.

These effects of corrosive influences upon fatigue

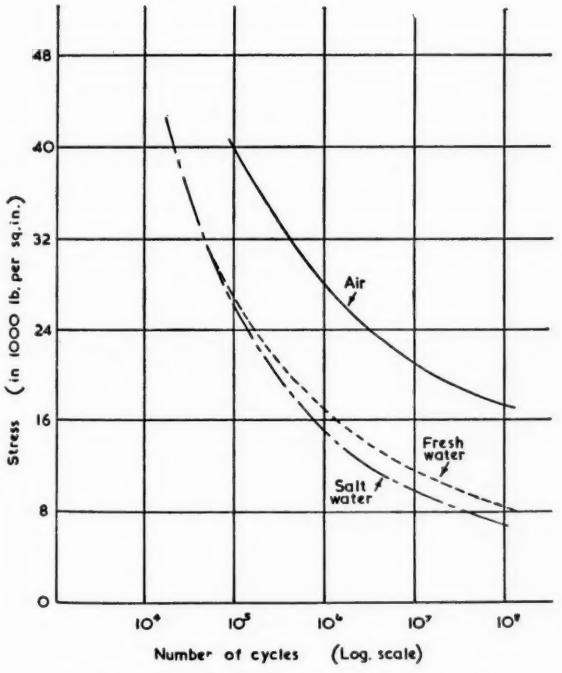

FIGURE 3. Corrosion fatigue curves for duralumin.

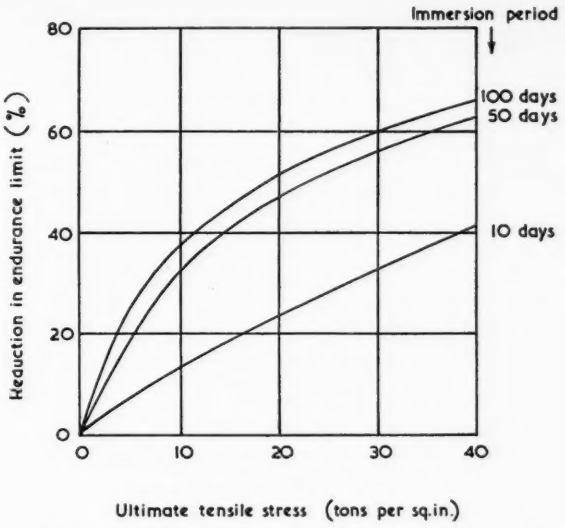

FIGURE 4. Effect of pre-corrosion on endurance limits of aluminium alloys.

may not always be on the debit side from the designer's standpoint. Gough and Sopwith[14] realised that tests *in vacuo* might show that conventional tests "in air" might themselves involve corrosive influences. They found that this was so, at least to a small extent; the endurance limit of duralumin, for example, was 6 per cent. higher *in vacuo* than in "air." More fundamentally, they also showed, as one would expect, that the presence of oxygen and of water vapour were key matters. Flight at high altitude may have advantages on these counts.

So far we have considered the effect of the presence of corrosive conditions *during* fatigue testing. The effect of exposure to such conditions *prior* to fatigue testing is also of interest. McAdam and Clyne[15] conducted a large number of such tests on a variety of metals, using water with the addition of some washing soda as a corrosive medium. Fig. 4 is based on their work, and refers to fatigue limits at 10^7 cycles for a variety of aluminium alloys. It illustrates the surprising, but generally applicable, fact that the corrosion "damage," so far as fatigue is concerned, is largely done in the first few weeks of immersion. It also shows how the stronger alloys are the ones most affected by pre-corrosion.

At this point a designer may feel that protective treatment is the answer; certainly the figures I have quoted have ignored this. So far as the effects of pre-corrosion are concerned, conventional protective measures are largely effective, although one should perhaps consider the possibility of local damage removing the protective covering. As regards corrosion-fatigue proper, however, protection is not so easy. Gerard and Sutton[16], in 1935, did some interesting work bearing on this. Tests were made on duralumin with various surface treatments, in air and under salt spray conditions. In air, anodic treatment actually appeared to raise the endurance limit (about ± 10 tons/in.^{2}) a little. Under salt spray conditions, for 10^7 cycles,

the untreated metal gave an endurance limit of about ± 3 tons/in.^{2} which was little altered by anodic treatment alone but raised to about ± 5 tons/in.^{2} when also coated with lanolin. Aluminium spraying, on its own, produced a comparable result of about ± 6 tons/in.^{2} at 10^7 cycles, but this fell off at a larger number of cycles. It appears that commonly available methods of protection against corrosion are, so far as corrosion-fatigue is concerned, only partially effective in salt spray conditions. Some very recent work, however, has shown a particular paint to give an aluminium alloy (H.10) very substantial protection against corrosion-fatigue[17].

I have mentioned these results in some detail—old and partial as they mostly are—not to suggest that corrosion-fatigue is a major factor affecting safety today so much as to bring it to mind when conducting or interpreting fatigue tests on aeroplanes and to make a plea for a revival of its study and an extension of past work to cover modern aeronautical conditions. Of particular structural importance would be corrosion-fatigue results for notched bars and for typical joints.

3. Thermal Effects

Rather over a year ago the Experimental Stress Group of the Institute of Physics held a conference at Bristol University to discuss thermal stress problems. Most of the papers then considered have since been published in "Aircraft Engineering," and others are now following in rapid succession.

In my own short contribution to that conference (unpublished), I tried to emphasise that investigations into thermal effects on structures are, in effect, making further contributions to the development of something like a "new mechanics" of deformable bodies, adding, after plasticity, both creep and temperature to the parameters of the classic theory of elasticity. Our position in this field is becoming somewhat analogous to that of the nineteenth century scientists in their development of the gas laws. The "static" pressure-volume law of Boyle was followed by the volume-temperature law of Charles; they were then jointly summarised by $pv = RT$, and finally raised to the status of an equation of state by van de Waal's equation, and so became a basic part of modern thermodynamics. If we discuss only linear thermal stress and strain problems, we are restricting ourselves to the Boyle's law stage of the subject. I pleaded, therefore, for more exploration of the non-linear and more dynamic parts of the thermal problem. Work of this sort was already apparent then and is now very considerable, and I would like here to draw attention to two of its aspects bearing on structural safety.

Short period effects due to rapid changes of surface temperature are likely to prove of considerable importance in aeronautical structures. Such rapid changes may arise in a number of ways; with manned aircraft, for example, descent at high speed after prolonged cruising at high altitude will give rise to rapid surface heating; the descent of long range ballistic rockets, such as the V.2, from great altitudes into the earth's atmosphere provides an extreme, almost meteoric, example. But more common, once aeroplane speeds approach Mach numbers of 2 or 3, will be the temperature change as the vehicle gains speed and altitude from the ground. In fact, for the ordinary ranges provided by the earth's airways, steady temperature conditions will be the rarity, and the problem will be to ensure, during the short time of flight, that temperature conditions at various parts of the vehicle, although continuously rising, do not reach certain critical values. The aircraft will, in effect, be judged for its safety in terms of its temperature endurance (in hours or distance) compared with the duration of flight or range required of it. Rendel and Hancock, of Farnborough, have discussed this matter recently in a very interesting way; the critical temperature, from our present point of view, is that governing the performance of the structure, and safety margins can be introduced—or ranges extended—by the introduction of refrigeration or of insulating coverings. It can be shown that without such amelioration, a skin temperature rise of 100 to 150°C. would occur for an aeroplane flying at $M=2$ for only 10 mins. This short endurance could, however, be transformed to a few hours by an insulating covering an inch or so thick. With such vehicles, just as for ordinary fatigue we discuss total flying hours in relation to fatigue life, so with critical thermal conditions—specified in terms of temperature limits—we may need to discuss safety in terms of flying time per flight in relation to thermal endurance.

A lot has clearly yet to be learnt about temperature limits, for the most damaging effects will be due to temperature gradients within the structure. The stresses due to these are both difficult to estimate and difficult to assess in effect, particularly when superposition of manoeuvring or gust loads is envisaged[18], and for some time to come relatively arbitrarily specified critical temperatures—such as a wing surface temperature—may have to suffice for the control of safety. No doubt an increased use of unmanned vehicles, for which safety is a less vital consideration, will help to build up empirical information ahead of experience with manned vehicles.

The temperature cycles thus arising in flight will, in the case of manned aeroplanes, tend to occur on every flight, corresponding to a condition of repeated thermal loading. For very high speeds, the peak temperatures in each cycle, and the internal stress distribution associated therewith, may be such that local plasticity and creep may occur, and the thermal cycle thus lead to progressive changes in the structure.

Effects of this sort have been studied theoretically both in America and this country. The maximum stress occurring in a wing of given material when the surface air temperature changes by T° is given approximately by $E\alpha T$, where E is Young's modulus and α the linear coefficient of thermal expansion. For an all-aluminium alloy wing, this stress, which occurs in the wing webs, is about 10 tons/in.^{2} for $T=100$°C., and for an all-steel wing, about 15 tons/in.^{2}. The response of the wing to repeated exposure to such temperature changes clearly depends on the relation of $E\alpha T$ to the margin $(p_y - p)$ between the yield stress p_y and the peak stress

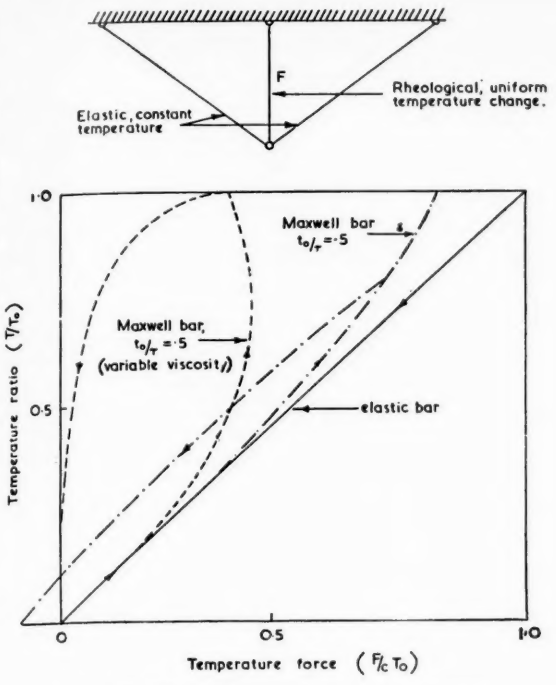

FIGURE 5. Effect of creep on temperature stresses.

p due to ordinary flight loads. Parkes, of Cambridge, has studied[19] the results of such repeated thermal cycles, assuming that full plasticity occurs wherever the total stress exceeds p_y. He finds that, if the thermal stresses $E\alpha T$ exceed the margin $(p_y - p)$ but do not exceed p_y itself, the structure will "shake down" to a state of elasticity; on the other hand, if the thermal stress $E\alpha T$ exceeds p_y, a condition of alternate plasticity leading to failure after a number of cycles, or a condition of increasing permanent deformation, arises.

Freudenthal, however, has pointed out[20] that the rheological behaviour—of which creep is an essential component—of real materials produces significant changes in the effects of a thermal cycle. When the effects of external forces alone are concerned, creep has little effect on the magnitude of the internal stresses produced by the external forces; but when we are dealing with a self-equilibrating system of stresses such as that due to a thermal change, creep and time play a major part in determining what internal stresses actually arise. In order to demonstrate this, and put the matter into quantitative form, he studied the simple redundant framework shown at the top of Fig. 5. For simplicity, the outer bars are assumed elastic throughout and at constant temperature, while the central bar has its temperature raised and is subject to rheological behaviour. The lower part of Fig. 5 shows some of his results for a temperature change first increasing from T_0 to T in time t_0 and then decreasing to T_0 again in the same time, both changes being linear with time. When rheological characteristics are allowed for, the behaviour of the structure depends on its "relaxation time," τ, which is proportional to λ/E, where λ is the coefficient of viscous traction relating stress to time-rate of strain.

It will be seen that for a visco-elastic bar (Maxwell bar) the effect of creep is to reduce the peak thermal stress arising in the cycle and build up a residual stress of opposite sign. If allowance is made for the variation of viscosity with temperature, the peak thermal stress reached is still further decreased. It thus becomes clear that the effects of thermal cycles on the internal stresses in a structure may be very complex, quite apart from any induced metallurgical changes affecting the fatigue properties of the material of the structure. To return to my gas analogy, to get far beyond the Boyle's law stage of this subject will clearly involve a great deal of very interesting but difficult work.

4. Concepts of Safety

Some technical aspects of two questions of current and future importance to the safety of aircraft have been studied. Consider now some developments and difficulties in the general philosophy of safety in the structural field. Writing in 1951[4] of the framework of this philosophy, I was apparently bold enough to say:—

> "It appears probable that, at least for the next decade, the fashionable dress will be that developed from the theory of probability, and that in its development concepts for yet a new dress will be found. At a guess, but one consistent with the pressure of economy at the present time, it may be expected that, just as the war-time form of the accident philosophy concentrated on accident rates with military efficiency in mind, so gradually the same concepts will take on forms emphasising economic efficiency, including, for example, allowances for maintenance and replacement. The whole machinery of statistics in the broad sense, and of quality control in particular, stands ready to assist this. Thus design may well become linked with the three philosophies, which it is hard to suppose humanity will ever fully unite—one aiming at minimising risk to human life, another aiming primarily at economic efficiency and a third aiming at military efficiency."

I have quoted at some length, I hope pardonably, because while the first part of what I then said—that regarding the linking of probability with economics—has largely proved true, the latter part regarding the improbability of any linking, for example, of the human and economic aspects of safety, appears in way of being shown to be, if not false, at least too pessimistic.

Consider some aspects of the first part. The whole machinery of modern probability theory has indeed been brought to bear on the subject, led by Freudenthal. Working mainly in the field of civil engineering structures, he has since 1947 published a number of major contributions, and now, in his "Safety and the Probability of Structural Failure"[8], produced a pocket treatise on the whole subject. Those who have at one time or another struggled with the application of probability theory to the problem will envy his facility. A standard problem of the past, for example, and one still of real interest, is the choice of load factor for a

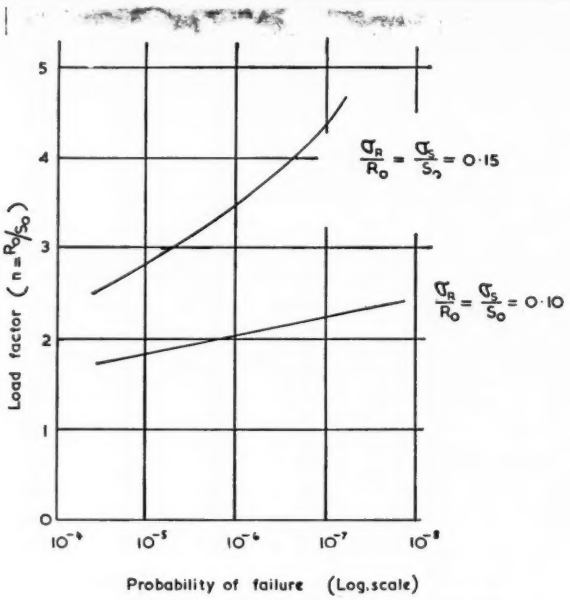

FIGURE 6. Effect of change of load factor on probability of failure.

given probability of failure due to over-loading, assuming relevant statistics of wing loads and wing strengths are known. If these statistics are distributed normally, the whole problem is now reduced to the delightfully simple quadratic relation

$$n^2\left\{1-\left(\frac{\rho\sigma_R}{R_0}\right)^2\right\}-2n+\left\{1-\left(\frac{\rho\sigma_S}{S_0}\right)^2\right\}=0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where n is the load factor, R_0 and S_0 are the means and σ_R and σ_S the standard deviations of strengths and loads respectively and ρ is a non-dimensional "radius" given by

$$\rho=2{\cdot}15\sqrt{-\log_{10}2\pi p_0} \quad . \quad . \quad (2)$$

Here p_0 is the probability of equality of the parameters R and S, where S will commonly involve a time element. For example, S may be the maximum load recorded on the structure per week, in which case p_0 will be the chance of equality of R and S in any one week. This probability p_0 bounds the area of the normal frequency curve defining the probability of failure P, and for the small probabilities concerned P is of the order of $0{\cdot}2p_0$ (*see* standard tables of normal distribution and frequency functions). It is interesting to use these equations (1) and (2) to plot curves for load factor n against probability of failure P for various values of the variances σ_R/R_0 and σ_S/S_0. Some such curves are shown in Fig. 6 and show how rapidly the risk of structural failure can be cut down by an increase of load factor. This is, of course, not new, but what is not generally realised is the great change of risk that must occur before it becomes noticeable to the users of aeroplanes. Structural accidents occur seldom and form only a small proportion of the total accidents to a given aeroplane type; under service conditions, even in peace, the structural accident rate has to be doubled or trebled before the change is sensed by service crews.

Equations (1) and (2) refer to cases of normal distribution, and can be depicted graphically. Similar, but not quite so simple, solutions exist for the important practical cases of normal-logarithmic and of extreme value distributions. For many practical problems, the three methods give roughly comparable results.

The linking of safety standards with economic efficiency has, since my earlier paper, been considerably advanced, particularly in Sweden by A. I. Johnson[6]. The general approach of all this work is to ignore human risks (or to assume we are dealing with structures that do not involve them) and aim to design the structure in the most economical way, allowing for its finite life and the need for its replacement on failure. Thus the structure provided on this basis is the one that makes the total cost of its maintenance (by periodic replacement or repair) for its given purpose a minimum. Quite incidentally, such a structure will have a definite failure rate, determined by costs alone. It is clear that the risks thus admitted may be considerably greater than those allowed in general practice, but the whole approach is obviously relevant to unmanned vehicles such as guided weapons.

If we continue to think in terms of probability of failure, it is convenient to cast the economic theory directly in terms thereof, as has been done by Freudenthal. If A is the initial cost of a structure, C the capitalised cost of its failure, and P the probability of failure during its life, then the economic approach aims to make the total $A+PC$ a minimum. In other words, the design is ruled by the equation

$$\frac{dA}{dP}+P\frac{dC}{dP}+C=0. \quad . \quad . \quad (3)$$

Now both A and C will depend somewhat on P, and if we express this thus

$$A=A_0(1-c\log_{10}P), \quad . \quad (4)$$

$$C=C_0+mA_0(1-c\log_{10}P)Q, \quad . \quad (5)$$

where m denotes the ratio between cost of reconstruction or replacement and initial cost, and Q is the factor of capitalisation appropriate to an interest rate i, then it is easy to show that, to a good approximation

$$\frac{1}{P}=\frac{C_0+mA_0}{cA_0}\cdot\frac{Q}{\log_{10}e}. \quad . \quad (6)$$

For a civil engineering structure, c may have a value of about 0·02 and the factor Q, for a life of 100 years and interest rate of 4 per cent., is about 25 (*see* tabulated values in Johnson's paper); hence from (6)

$$\frac{1}{P}\doteqdot 3{,}000\left(\frac{C_0}{A_0}+m\right). \quad . \quad . \quad (7)$$

Thus $1/P$ tends to vary linearly with C_0/A_0. Since C_0 includes all the direct and indirect losses due to failure, C_0/A_0 will often exceed m, which will commonly have a value in the region of 1 or 2. Taking $C_0/A_0=2$ and $m=1$, (7) gives $P=1$ in 9,000; in other words, it would be economic to design the structure so that, if 9,000 such were built, one would fail in the course of its life.

I have here drawn attention to this form of analysis because I now want to use it to make what is perhaps

a new point, or at least a new way of stating an old, yet still pressing, difficulty. The economic approach has, I believe, partly developed so rapidly because none of us working in this field has yet seen an acceptable and rational way of handling the human aspect of the safety problem. As my earlier quotation shows, I was at that time inclined to suppose that we never would. Recent large scale accidents, however, have brought to mind an approach to the difficulty that, though economic in form, is human in basis. It is this. When a small aeroplane crashes and its one or two passengers are killed it is regrettable, but the rest of the world treats it as motor car accidents are commonly treated. Even if the accident is shown to be due to structural failure, unless there is a rapid succession of such accidents, the public reaction is still small. When, however, a large civil aeroplane with some 50 passengers crashes, and the failure is clearly a structural one, the reaction is not only national but international. A second such accident brings such pressure to bear that the whole fleet of aeroplanes may be grounded. The overall effect, though not deliberately economic, can be measured in economic terms, and we seem to have here an empirical basis for a discussion of human risks as set by the public sense of human values.

Let us consider two extreme cases, one relating to a small non-passenger carrying aeroplane (*A*), and one to a large civil aeroplane (*B*) of the type just mentioned.

For both aeroplanes, Q, c and m in equation (6) will be about the same, but if we restrict attention to structural accidents only, C_0/A_0 will be some 10 or 20 times greater for aeroplane (*B*) than aeroplane (*A*), and would be larger than one in both cases. Were structural accidents the only type of failure, equation (6) would therefore suggest that, to satisfy public opinion, the structural accident rate for aeroplane (*B*) should be about 1/10th that for aeroplane (*A*). In fact, however, there are commonly many more serious accidents to aeroplanes for non-structural than for structural reasons, and this applies perhaps particularly to aeroplane (*B*). Nevertheless, even when an attempt is made to allow for this, the demand, expressed by our analysis in economic terms, is still for a relative decrease of the structural risk, as between (*B*) and (*A*), of at least 3 to 1. This order of change does not, of course, involve a correspondingly large increase of load factor for the large aeroplane; from Fig. 6 and similar evidence it is clear that an increase of 10 per cent. or 20 per cent., appropriately applied, might cover the difference.

I come here to my last point. Civil engineers have for long been accustomed, subconsciously or otherwise, to provide somewhat greater margins of safety, however expressed, in cases where human life is peculiarly at stake or when the economic effects of a structural failure would be great. The committee of the Institution of Structural Engineers, to which I earlier referred, has reviewed such allowances so far as load factors are concerned, and tried to state them empirically in numerical terms[21]. In other words, it has aimed to bring out into the open and start to rationalise deliberate provision for the "seriousness" of a failure, whether measured in human or economic terms; and it is interesting that the allowances suggested, though not in the same form, cover a greater range than the "large air liner" reserve factor of 1·1 or 1·2 deduced by the economic-cum-probability argument that I have just outlined. Since we cannot sense a change of aeronautical structural accident rate until it reaches roughly a 3 to 1 ratio, it may be that the probability of structural failure, as between a small non-passenger carrying aeroplane and a large air liner, should have a ratio of more nearly 10 to 1. The accident rates from other causes may tend to even out this specialised difference. All this requires further argument; what I hope is that we are seeing the beginnings of simple and acceptable ways of linking human and economic risks in our philosophy of structural safety.

There is, of course, one aspect of this matter that will cause heart-searchings among us. To adopt different probabilities of failure, however small in themselves, seems to make distinctions between small and large aeroplanes, or between one passenger and fifty, as regards standards of safety. I can only point out that such distinctions would relate only to structural accidents and have, as a matter of history, been made before in other fields of both structural and transport engineering, and that the general public, both national and international, appear to react in that way. We are here at the ethical basis of our subject; in safety matters, as J. D. North has often wisely pointed out to me, we are all contributing to "a social judgment." The conflict, if conflict there is, is between the "purely ethical" view and what may be called the "purely biological" view; aircraft designers are here, as perhaps not infrequently before, facing an engineering version of the modern "doctor's dilemma" with regard to the use of precious drugs.

A practical approach at the present time would perhaps be to say that (assuming the airworthiness of current small aeroplanes is satisfactory) with large new civil air liners, particularly those with rather experimental features, every effort should be made to ensure that their probability of structural failure is less rather than greater than for the conventional small civil aircraft; that to ensure this it may be necessary to expend more money, skill and time on structural calculations and proving tests. Sometimes too it may be wise to lower general stress levels, whether measured by a reserve factor or not, or to resort to a greater use of redundant structures to provide alternative load paths; and so on. This, rather than a strictly numerical approach, is perhaps the wise way of stating the matter today.

REFERENCES

1. PUGSLEY, A. G. and FAIRTHORNE, R. A. (1939). Note on Airworthiness Statistics. A.R.C., London, R. & M. 2224, 1939.
2. PUGSLEY, A. G. (1942). A Philosophy of Aeroplane Strength. A.R.C., London, R. & M. 1906, 1942.
3. WALKER, P. B. (1953). Estimation of the Fatigue Life of a Transport Aircraft. *Journal of the Royal Aeronautical Society*, London, Vol. 57, October, 1953.
4. PUGSLEY, A. G. (1951). Concepts of Safety in Structural Engineering. *Journal of Institution of Civil Engineers*, London, Vol. 36, 1951.

5. PROT, M. (1948). La Securité des Constructions. 3rd Congress, International Association of Bridge and Structural Engineering, Liège, 1948.
6. JOHNSON, A. I. (1953). Strength, Safety and Economical Dimensions of Structures. *Meddelander* 12, Inst. of Byggnadsstatik, Roy. Inst. of Technology, Stockholm, 1953.
7. FREUDENTHAL, A. M. (1947). The Safety of Structures. *Trans. American Society of Civil Engineers*, New York, Vol. 112, 1947.
8. FREUDENTHAL, A. M. (1954). Safety and the Probability of Structural Failure. *Proceedings American Society of Civil Engineers*, New York, Vol. 80, 1954.
9. PUGSLEY, A. G. (1947). The Behaviour of Structures under Repeated Loads. *Journal of the Royal Aeronautical Society*, London, Vol. 51, 1947.
10. FREUDENTHAL, A. M. and GUMBEL, E. S. (1953). On the Statistical Interpretation of Fatigue Tests. *Proceedings of the Royal Society*, London, A., Vol. 216, 1953.
11. PROT, M. (1948). L'essai de Fatigue sous Change Progressive. *Rev. Metall.*, Paris, 12, 1948.
12. FREUDENTHAL, A. M. (1954). A Random Fatigue Testing Procedure and Machine. *Proc. American Society for Testing Materials*, New York, Vol. 54, 1954.
13. MCADAM, D. J. (1927). Corrosion-Fatigue of Non-Ferrous Metals. *Proc. American Society for Testing Materials*, New York, Vol. 27, II, 1927.
14. GOUGH, H. J. and SOPWITH, D. G. (1935). Some Further Experiments on Atmospheric Action in Fatigue. *Journal of Institute of Metals*, London, Vol. LVI, 1935.
15. MCADAM, D. J. and CLYNE, R. W. (1934). Influence of Chemically and Mechanically Formed Notches on Fatigue of Metals. Bureau of Standards, *Journal of Research*, Washington, Vol. 13, 1934.
16. GERARD, I. J. and SUTTON, H. (1935). Corrosion-Fatigue Properties of Duralumin With and Without Protective Coverings. *Journal of Institute of Metals*, London, Vol. LVI, 1935.
17. INGLIS, N. P. and LARKE, E. C. (1954). Corrosion-Fatigue Properties of an Aluminium-Magnesium-Silicon Alloy in the Unprotected, Anodized and Painted Conditions. *Journal of Institute of Metals*, London, Vol. 83, December, 1954.
18. LOVELESS, E. and BOSWELL, A. C. (1954). The Problem of Thermal Stresses in Aircraft Structures. *Aircraft Engineering*, London, Vol. XXVI, April, 1954.
19. PARKES, E. W. (1954). Wings under Repeated Thermal Stress. *Aircraft Engineering*, London, Vol. XXVI, December, 1954.
20. FREUDENTHAL, A. M. (1954). Effect of Rheological Behavior on Thermal Stresses. *Journal of Applied Physics*, New York, Vol. 25, September, 1954.
21. Report on Structural Safety (1955). *Journal of the Institution of Structural Engineers*, Vol. 23, May 1955.

DISCUSSION

N. E. ROWE: He felt that he had been sitting in a refreshing breeze. They had heard a fascinating lecture presented with great lucidity on a theme which was not normally touched on in such a wide and philosophic way. For aeronautical men he thought that the approach was unusual. It had been very stimulating and he looked forward to an animated discussion.

F. W. PAGE (English Electric Co. Ltd., *Fellow*): As he had known Professor Pugsley for many years and had long admired his outstanding ability he wished to add his own personal welcome and tribute to what had already been said. It was characteristic that Professor Pugsley had been able to present a very complex subject, introducing many new and challenging ideas, in remarkably small compass.

Statistical and probability concepts in relation to structural safety were now more generally accepted: as regards fatigue, they were already accustomed to using, in a limited fashion, the compromise test procedure put forward by Professor Pugsley, that was the use of the cumulative damage law cycle with the insertion, at appropriate intervals, of a few cycles of large amplitude loads, and the necessary apparatus was available to obtain an even closer representation of a complete and thoroughly representative duty cycle. He did not think that they used this approach to anything like the extent that they must in the future.

They were also getting accustomed, for thermal effects, to considering reproducing duty temperature cycles in ways that bore some relation to fatigue and of course, systems testing; indeed it had already been concluded, at least on very high speed aircraft, that time was a dimension which most certainly could not be omitted, not only from the point of view of structural design but also from the point of view of system functioning and overall design efficiency. There was no doubt that the rate at which maximum speeds of aircraft were increasing, was forcing the designer to take a practical interest in thermal effects and Professor Pugsley might detect less resistance to new conceptions in this respect than he had encountered in the past in relation to fatigue.

Apart from the complexities of thermal stressing, so admirably brought out in the lecture, there was the very real practical problem of designing for thermal stress cycles in conjunction with the normal aircraft loading cycles. To attempt to put safety factors on both cases independently and then add them would, he thought, for a variety of reasons, lead to a very uneconomical design. It was already becoming necessary in practice to consider critical parts of the aircraft and test them under a combination of repeat loadings and temperature cycles. A thorough programme on the broad lines indicated by Professor Pugsley to gather experimental data and to provide a sound theoretical basis on which design could proceed was, he thought, urgently required if large *ad hoc* test programmes and uneconomical design were to be avoided. These large test programmes were, of course, expensive.

On the general conception of structural safety, there was no doubt that economic efficiency, as Professor Pugsley suggested, should properly be determined by a balance between risk and efficiency; and the approach to the question of risk that had been advanced in the paper, although novel, certainly seemed sound and one which was not likely to cause undue difficulty in application. He would, however, suggest that there were only these two parameters involved, namely risk and economics. In the paper a separation was suggested between military efficiency and civil economics but he thought that under the weapons system concept in military aircraft,

military efficiency could be analysed in precisely the same terms as commercial efficiency, although the numbers and terminology involved might be rather different.

Having suggested a possible simplification in one direction, however, he was afraid there might be complications in another in carrying the question of rational design to its logical conclusion. There was an increasing tendency to issue requirements of all kinds, both civil and military, without due regard to this proper balance between risk and efficiency judged on a statistical basis. If Professor Pugsley could suggest some way in which the issuing of new requirements, not merely structural but those relating to systems and other matters, could be assessed in terms of safety and economics, it would be a very great step forward to improved overall design efficiency.

There were three detailed points to which he wished to refer.

First, the fatigue properties of high strength aluminium alloys of the 75 S-T type referred to early in the lecture: the mechanism by which this proceeded had been demonstrated by F. R. Hanstock of High Duty Alloys and, as in all cases where a problem was understood, there might perhaps be a hope that they would eventually solve that problem and obtain reasonable fatigue properties, together with high static strengths. The work by Mr. Hanstock also suggested that there was a very real basis for the cumulative damage law, in that he had found that the fatigue developed by the accumulation of precipitation products in crystal boundaries.

Secondly, as regards thermal effects; the maximum stresses quoted by Professor Pugsley for aluminium and steel could be expressed in terms of percentages of the proof stress. For aluminium they amounted to 34 per cent. of the proof stress per 100°C temperature rise, and 24 per cent. for steel. There was one omission in these materials, a new material to which they were becoming accustomed, namely, titanium and it was surprising that on this basis the corresponding stresses in titanium amounted to only 11 per cent. of the proof stress. That might be a significant advantage in the use of titanium in high speed aircraft which had not been apparent hitherto, but which might be significant in the future.

Lastly, looking rather far into the future, the control of thermal effects might be aided by the use of a thermometer as one of the primary flight instruments in place of the conventional Mach-meter or air speed indicator. This idea, although perhaps a trifle revolutionary, had many practical virtues but no doubt all the people concerned would take a lot of convincing.

E. LOVELESS (English Electric Co. Ltd., *Associate Fellow*): It would appear that the time had now arrived for a new and searching enquiry into aircraft loading conditions.

Previously they had a flight envelope and gust cases (as the principal symmetric flight cases), both arrived at from consideration of speed and acceleration records with tolerances and factors applied from statistical evidence.

Professor Pugsley had pointed out that to ensure a lower accident rate for large aircraft they might need a 10-20 per cent. increase in load factor, or a decrease in stresses, whichever way one wished to use it. While the designer must be extremely careful about structural failure on both moral and economic grounds, an increase in load factor was not a thing which could be lightly contemplated because it meant a higher weight and probably an increase in overall dimensions and, of necessity, it meant a lower payload and performance.

The difficulty of truly representing loading conditions and the large scatter of results during fatigue testing had been mentioned, but he felt that an even greater source of error could be in the assessment of anything like the true loading conditions during flight which had to be applied during testing. This estimate was extremely difficult, both for the gust and manoeuvre loadings to apply to the overall structure, although investigation was now being made by means of fatigue meters and counting accelerometers fitted to both civil and service aircraft. For components like power controls and hydraulic services which were operated at frequencies depending entirely on the type of mission being undertaken, as well as air turbulence conditions, and so on, a true assessment of the loadings applied was extremely difficult and much more statistical evidence was required.

Again in regard to thermal stress effects, for both transient stresses due to thermal gradients in the structure and reduction in material properties due to heating the structure for prolonged periods, or a summation of shorter periods, it was essential to know the temperatures and changes of temperature to be designed for and the combination of these with the overall air loadings.

It was easy to make pessimistic assumptions to cover these cases so that everyone was covering themselves, and while this might lead to structural safety it might lead to an uneconomic aeroplane; he felt that a new approach must be made by marking out a typical flight plan. He realised that it was easy to say "a typical flight plan," but it was far from easy to define. For a civil aircraft operating on a given route the flight plan was more or less definite, but if it changed to another route, that plan was changed. For military aircraft the operating conditions were changed from mission to mission, hence the difficulty.

It was no use introducing refinements in stressing methods of structural analysis to obtain increased performance (at the same time reducing the well-known Stressman's safety margin), unless the loadings on which the stressing was based was very carefully determined by a lot of statistical work.

B. O. HEATH (English Electric Co., Ltd.): To design structures for a given life would induce safety consciousness more than did the negative task of designing against an accident rate. The public would surely prefer to know that air liners were designed for a given life and then replaced, rather than to find their worst fears confirmed by discovering that there was an "official" accident rate, which would not be correctly interpreted by those who preferred "to keep one foot on the ground"!

The fatigue results shown were encouraging but the problem was still a very difficult one for random loads. Nevertheless the duty cycle concept had been specified officially for power controls and similar experimental work applied to structures might prove equally rewarding.

On very high speed military designs subject to high temperatures, fatigue was relatively less severe, not because the fatigue properties themselves improved, but because transient temperature stresses, creep and lowered steady state strength and elastic moduli all became worse. It would not be very long before aeroplanes appeared in which the skin temperatures stabilised, as it was not always easy to add the odd inch of insulation, due to wave drag considerations. In applications where fatigue and temperature problems were both important, redundant structures had an appeal when designing against fatigue, but might be undesirable under transient heat conditions.

Professor Pugsley had implied by his triangular frame example (as American authors had stated directly) that even the instantaneous temperature distribution was not enough to specify the stress distribution throughout the structure. Ideally, not only the history of any particular flight was needed but that of all those preceding it. He would like some idea, if Professor Pugsley could give it, as to what extent this principle should be respected for practical stressing.

Mr. Loveless had mentioned the intricacy of stressing to a flight envelope. Loads must be found for an aeroplane often with non-linear servo mechanism, structure and aerodynamics, manoeuvred (on paper or simulator) to the boundary of a flight pyramid. To define worst stressing cases pressure plots which were consistent with the aerodynamic derivatives and stiffness of the structure were needed. If to this difficult task were added considerations of temperature history (possibly in several climates!) a labour force was implied which was so vast, yet specialised, as to be unobtainable in this country.

Professor Pugsley had said that structural accidents formed a small percentage of the total; he would suggest that, if military designs were considered, flutter incidents were most frequent. A flight plan-duty cycle approach might enable a fair allocation of labour still to be made to such problems, and might even save weight and complication by eliminating unlikely cases.

It was seen to be a difficult problem to assess the safety of an aeroplane which was placed before the technician on paper. What a task to put there at all, since this involved solutions to all the problems mentioned, plus the integration with economic and production considerations! If there were no previous experience, neither statistical approaches nor any disguised guess work would really help.

In the missile field, a scientific form of cut and try technique was being used. The missile designer might fire off a hundred rounds and obtain a statistical failure rate.

For aircraft there would have to be acceleration of detail calculations, and earlier testing involving greater use of models and of simulators. Such aids were worth vast efforts on operations research, based on dubious quantities.

MR. RHODES (English Electric Co., Ltd.): The lecture had emphasised the enormity of the fatigue problem in a very striking manner. It was frequently said that to increase the fatigue life of a structure it was only necessary to design to a higher load factor. However, this sort of approach was not likely to lead to efficient lightweight structures. For instance it would be folly to increase the cross-sectional area of a complete spar boom because of a low fatigue life of the end attachments.

Indeed there were cases where designing to a higher fatigue factor could result in a reduced fatigue life. As an example, consider a pressure cabin structure in which the skin gauge was decided by criteria other than strength (such as a non-buckling skin). Then an increase in the design factor, say from 1·5 to 2, might result in a closer pitching of the rivets, a reduction in the effective skin area across the rivet line, and consequently a reduction in the fatigue life. This argument could apply at any skin joint throughout the structure and since most structural fatigue failures were initiated at joints it was an important consideration.

Professor Pugsley had gone to some lengths to discuss the present dilemma of the structures engineer. As speeds increased he had not only to ensure adequate strength and stiffness under conditions of accelerated flight, but also to cater for transient thermal stresses and creep. Meanwhile the strength of the materials at his disposal was falling with elevated temperatures. He thought that the main difficulties lay not in the actual calculation of the thermal stresses so much as:—

(*a*) The estimation of the temperature gradient.
(*b*) The precise knowledge of the temperature-time history in conjunction with flight loads.
(*c*) The maze of possible design cases which would arise as a result of this.

In brittle materials such as glass, the problem of transient temperatures and thermal stresses was undoubtedly of paramount importance. In the plasto-elastic materials of aircraft structures, however, conditions were nothing like so severe and, provided that they guarded against the possibility of thermal and creep buckling, they would always have plastic flow to vitiate the stresses. This, however, would inevitably lead to permanent deformation and it seemed to him that if they were to design successful aircraft capable of operation at Mach numbers greater than 2, then a considerably more permanent set might have to be accepted. It had been suggested some time ago that the proof condition was the important criterion to design to. He would suggest that they had now reached a stage in aircraft design where the so-called proof failure no longer had much significance. All aircraft had to be designed for stability and of course airworthiness in accelerated flight; that was in a deformed condition. Surely therefore they could accept more permanent structural deformation?

Regarding the choice of load factor for a given

probability of failure due to over loading, in Fig. 6 Professor Pugsley had drawn a graph which indicated a significant reduction in the failure rate by small increase in the factor. If they worked to the case of a given aircraft design by assuming a given value of load deviation and probability of failure, then a curve showing the effect of increase in strength deviation against required design factor also showed significant effects. Thus for a probability of failure of one in 10^6 and a load variance of 1·5, then zero strength variance gave the value of $n = 1{\cdot}75$, while for strength variance of 0·16 the load factor was 4. Since present-day machines could have growth factors of the order of 20, he would suggest that it would be far more economical to reduce the sub-standard variation in strengths by modifying and improving the inspection procedure, rather than design to an increased factor.

He felt that they had reached a stage in aircraft development where the whole question of safety factors should be reconsidered, with a view to their unification and reduction and that the required fatigue life and the load frequency spectrum should become as much a part of the design requirements as the flight envelope. The whole question of fatigue factors would then be left to the responsibility of the designer.

J. C. KING (English Electric Co., Ltd. *Associate Fellow*): In 1942 when he was a member of Professor Pugsley's staff he first read the paper referred to in the introduction on the philosophy of aeroplane strength and was immediately struck by the logical concepts contained therein. Little did he realise at the time the extent to which the probability theory and philosophy would be applied in the years ahead.

Professor Pugsley was no doubt familiar that this approach was not restricted to aircraft structures. In some recent draft performance requirements for civil aircraft it was proposed to base the calculation of engine safety speed, runway distance, etc., for aircraft operating at a given weight, on the combined probability arising from the known frequency of engine failure and the frequency of specific wind and runway surface conditions. There was no doubt that the lecturer was instrumental in sowing the seed of the probability approach to all these problems in the minds of many aeronautical engineers, and he must be congratulated on such pioneering work.

Reference was made in the section on fatigue to the effect of atmospheric conditions on the fatigue properties of materials, but he did not think it was out of place to mention that a considerable programme of work was in hand in Great Britain on the effect on the stress corrosion (as distinct from corrosion fatigue) of D.T.D.683 high strength aluminium alloy, of chemical composition, surface treatment and heat treatment. His firm's contribution to the work was shown in Fig. A giving a graph of the time to failure of specimens stressed across grain in pure bending against the extreme fibre stress. These showed that there were two types of chromium-free material, namely, that susceptible to stress corrosion, the points for which fell in the bands on the left of the graph, and unsusceptible

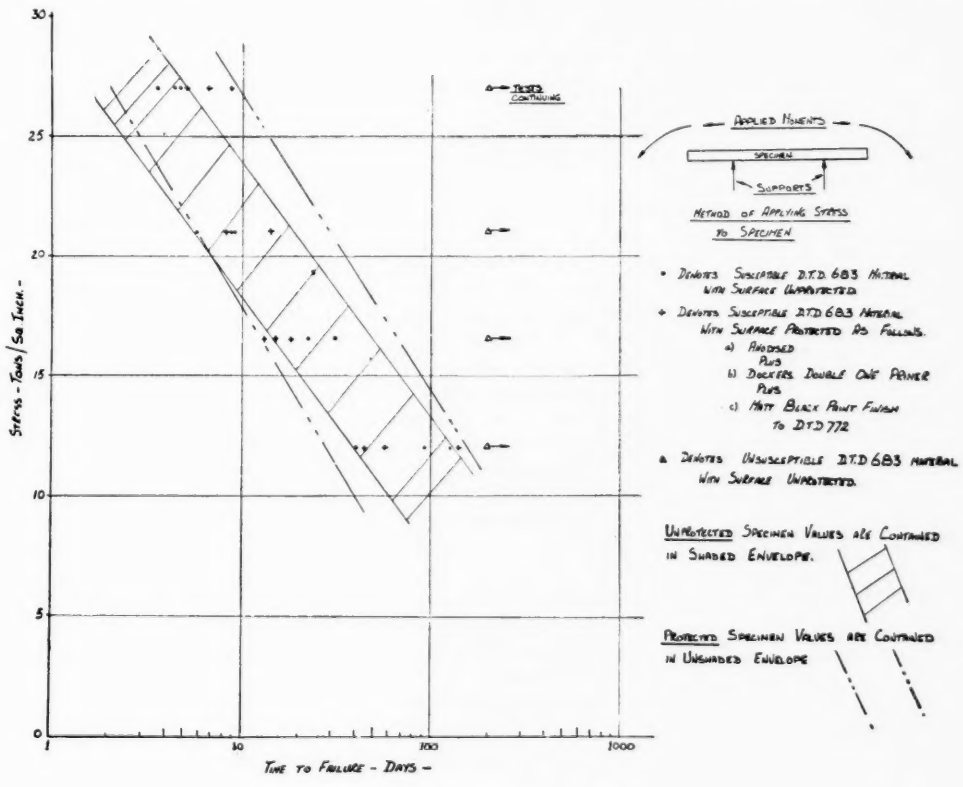

FIGURE A. Stress corrosion time relationships for D.T.D.683 (chromium free).

material, the points appearing on the right. It showed further the rather unexpected result that for both protected specimens and unprotected specimens, the time to failure was substantially the same.

It would be appreciated that stresses as low as 10 tons/in.^{2} leading to failure in as short a time as 50-60 days, were often present in hydraulic components, as long as they were pressurised which could be for the whole service life of the aeroplane, or on undercarriage mechanisms whenever aircraft were standing on the ground. Considerable care, therefore, had to be taken to avoid these continuously, or semi-continuously, applied stresses occurring across grain. It was normally satisfactory if they occurred down the grain. This was just another problem involving stress, time, environment, surface treatment and metallurgical conditions.

These problems, together with those described by Professor Pugsley, made him doubt whether theory would ever be able to keep up with the development of aircraft. This was not a criticism of theory because it was only by that that engineers were able, initially, to think logically about their problems and, later, to obtain reliable quantitative estimates of stress, and so on. Nevertheless supersonic aircraft and even supersonic transport aircraft which introduced further time dependent variables could not be so very far behind. It might well be that theoretical methods would not be sufficiently advanced when these aircraft arrived to provide adequate estimates of stress or life.

These thoughts, coupled with the ever-increasing environmental testing that had to be done on aircraft structures, fuel and hydraulic systems, made one wonder whether structural life testing of complete aircraft would not become a " must " for aircraft designers. In other words, the glorified *ad hoc* testing Mr. Page had mentioned was, he felt, bound to come. Indeed, it was almost with them already. Was it not time, therefore, to think of building a facility for this work in the form of a vast air-conditioned hangar with repeat loading and other test devices inside? A rough estimate of the air supply necessary for this work was in the order of 1,000 lb. air per second, that was five to eight times the mass flow through the largest jet engines. It would be realised, therefore, that he was thinking of an extraordinarily large facility, similar to that installed by the Germans at Munich for high altitude testing of their jet engines at the end of the 1939-45 War. In Great Britain they had suffered many delays became no such engine testing facility was built after the end of the war, and he thought it was not too early now to be thinking seriously of a similar facility for airframe testing. As Professor Pugsley had always taken a particular interest in experimental methods, he would appreciate his views on this suggestion.

MR. N. E. ROWE: He had heard another lecture at Bristol* recently in this general field which had at this time such significance for the future design of aircraft. Some of the same ground had been covered this evening but from a different point of view. Personally he was impressed by two very important things. One was the nature of the aluminium alloy material they dealt with in aircraft and the need to obtain a physical idea of what went on under repeated loading in that material and he thought that, until they did, they would be in grave difficulties. The other was the effect of scatter on the structural provision which had to be made; if the uncertainty which arose from this could be reduced then clearly this would mark a great advance. The scatter arose from uncertainties in the behaviour of the material because they could not understand it, and from the nature of the load system. With regard to the latter it had struck him that perhaps they gave up too soon the work that was done on gust alleviation. Gust loading was most certainly one of the major effects on civil aircraft in producing these fatigue actions and he felt that it would pay them to put a great deal into research on gust alleviation because it could reduce one area of scatter completely and hence, perhaps, give big rewards.

It was a great pleasure to be here at a Branch at a Main Lecture and it also did another thing for him personally; it discharged part of a duty which he had laid on himself to visit all the Branches during his period of Presidency-Elect and Presidency. Major Bulman, when he was President tried to do the same thing, that was just during one year and very gallantly he failed by one Branch, which was a magnificent performance. He had given himself rather more time to do it in and still found it difficult enough; so if they would kindly take this as his official visit to the Branch he would be most obliged.

He did not think there was any need for him to say what he had said so often about the feeling of the Council on the work of the Branches, on the tremendous job they were doing and the increasing importance of it. He thought they were unique in the professional and learned Societies in the constitution of their Branches in that they were not all members of a professional body but embraced a much wider group of aeronautical men; the level of Lecture Programmes had gone up tremendously over the past years and was a great and growing factor in the strength of the Society, so that he personally, as Chairman of the Branches Committee, felt great gratitude to the work of the Branch Officers.

It was a great pleasure to propose a vote of thanks to the Lecturer that evening. He had given a lecture which he was sure would be referred to again and again. It embraced ideas and concepts which were peculiarly Professor Pugsley's own which he had developed over the years and which had been carried to a further stage that evening. The appeal of these concepts to the modern structural engineer had been demonstrated most clearly, he thought, by the liveliness of the discussion, by the varying points of view that were put and by the clear ideas that the young men of the Society had of the importance of the statistical approach. He thought personally that the statistical approach might be accepted readily by the public since no individual thought of himself personally as the "one chance in 'x'"! If the statistic about bathing in the sea was that one in

*The Present Outlook on Fatigue: The Second Barnwell Memorial Lecture. WALTER TYE. *Journal of the Royal Aeronautical Society*, May 1955.

ten thousand got drowned per annum, no one person ever thought he was that one. If statistically "y" people lost their lives in aircraft accidents annually intending passengers never said to themselves as they went aboard the aircraft "Well this is it" because if they said that, they would not go. So that he thought the statistical approach so lucidly presented by Professor Pugsley might well be accepted and it seemed to be an extraordinarily sensible one.

He felt that they had been privileged to listen to a really classic lecture and he asked the audience to show their appreciation in the usual manner.

A. DONKIN (Stress Office, English Electric Co. Ltd.) *contributed*: Statistical analysis in the past had shown that only a small percentage of serious accidents was due to structural failure—this was very heartening to the aircraft structural engineer. The thought, however, of designing an aircraft type with odds of, say, 100 to one against one crashing due to structural failure during its service life was certainly not heartening or easily acceptable.

With their present knowledge fatigue damage could not be detected until a crack occurred, and even then it might not be in an accessible or easily visible position. In designing an aircraft, therefore, they must estimate the resistance of its structure to the repeated loads to which it was subjected. With a structure in its design stage estimates of life could be based on available comparative data only. This could broadly be divided into three sections:—

(*i*) Tests on standard test pieces;

(*ii*) Tests on small components;

(*iii*) Tests on major assemblies or complete aircraft.

Considerable fatigue information was now available for common materials in the form of standard test pieces, but even in these elementary tests they were faced with a degree of scatter which at first sight was alarming. The figures quoted by Professor Pugsley for 75 S-T showed that for a cyclic stress of 60 per cent. of the ultimate the life could vary by 7 times, and at a cyclic stress of 40 per cent. of the ultimate the life could vary by as much as 270 times. The variations were due to inconsistencies in many factors—the material composition and structure, surface finish, protective treatment, mode of testing and corrosion were some of the more important ones, and all of these had a varying effect on the fatigue strength.

If these factors were fully understood they could presumably make an accurate assessment of fatigue life—unfortunately they were far from this happy state of affairs.

In detail design the problem of accurately assessing the fatigue life of a small component, skin joint, and so on, by calculation was not yet possible but the problem of designing to a safe stress for a given life was not so formidable. This was particularly true in the low stress level range where a very small change in stress could give an enormous increase in life.

A similar problem existed in the testing of major components (wings, pressure cabins, etc.) although it was more serious because of the expense limitations on a large number of tests. However, by testing a specimen at a factored stress level and obtaining a life, they could give a safe life with much more confidence than they could have done had they tested at the nominal stress level. This was at least true in the low stress level range, and was used in the design criterion for wings suggested by Walker, in which a factor of 1·25 was applied to the loading due to an 8 ft./sec. gust. Difficulties occurred if a stepped load pattern were selected for testing a component, but even the steps might be factored.

The value of the factor to use would have to be obtained from a comprehensive set of tests on typical structures at various stress levels. The structures could be simplified however—for example the factors to be used on pressure cabins could be obtained from a cylindrical structure typical of a pressure cabin. Present knowledge on the degree of scatter of complete assemblies was seriously inadequate if they were to have both structural safety and structural economy

DR. S. S. GILL (College of Technology, Manchester) *contributed*: Although the idea of applying probability theory to the estimate of the safety of structures was becoming more acceptable, the old ideas of stress factors of safety still persisted. Aeronautical engineers had some advantage in that they had used load factors of safety from early days. It was unfortunate, however, that they still met text books where riveted and welded joints were tacitly analysed by an "ideally plastic" theory using a stress factor of safety, and "working" stresses for which the real stress distribution would be elastic. These anomalies would almost inevitably continue, but they were indebted to Professor Pugsley in this country and to Professor Freudenthal in America for their advocacy of the logical approach to safety as the probability of either failure (structural damage) or the probability of unserviceability (functional damage).

In comparing the two types of damage, it was important to consider the ratio

$$\frac{\text{failure load}}{\text{proof load}} \quad \text{or} \quad \frac{\text{load to cause structural damage}}{\text{load to cause functional damage}}$$

for the structure. This ratio was dependent on the type of structure and the material used. As a simple example, the ratio for a mild steel beam in bending was 1·5 for a rectangular section, and about 1·15 for an I-section. If both beams were designed for the same probability of functional damage (specified maximum permanent deflection), the probability of failure would be very different for the two beams. It might be good policy to have a much higher probability of functional damage than of structural damage as a convenient warning device. This idea had often been used in all types of engineering. The decision on the merits of designing for the two types of failure was dependent on the relative frequency of the loads to cause structural or functional damage, the type of structure and the costs of repairs.

Since such decisions must involve the collective judgment of a whole group of experienced engineers, it

was essential that they be embodied in specifications or standard codes of practice and strength requirements. The probability of failure by fatigue loading, brittle fracture and the problem of plastic "shake-down" would need consideration.

He felt that because of the shortness of his paper, Professor Pugsley had been unable to show the full implication of the new concepts of safety. It seemed inevitable that in designing for prescribed probabilities of structural and functional damage for a given structure, and considering all the possible modes of failure, the demands on the aircraft stress office would increase considerably. While Professor Pugsley's approach to safety was the only possible and rational answer, it must surely lead to many more "stressing cases." This implication must be faced and it was unfortunate that due to the limited length of the paper only a few of the types of problem involved could be discussed.

In his recent paper, Freudenthal[8] mentioned briefly the insurance rates for trans-Atlantic flights. It would be interesting to have more information of this type and to compare the probabilities of failure computed by the insurance company actuaries with those computed by structural engineers.

P. M. HUGHES (English Electric Co. Ltd., *Graduate*) *contributed*: The title of the paper was "Structural Safety" yet its contents referred entirely to structural failure! It might seem trivial to raise a point like this but it suggested that a more positive outlook could perhaps be adopted. This might well have a less demoralising effect on designers, intending passengers and air crew alike. For instance, instead of discussing probabilities of failure, turn the figures upside-down; that was, use the reciprocals and call them improbabilities of failure. Equations 6 and 7 in the paper pointed towards this suggestion. Fig. 6, although it might not be obvious at first, was actually drawn in this sense. The horizontal logarithmic scale represented probability of failure but it defied convention and descended from left to right. The range was from 10^{-4} to 10^{-8}. Now without altering the curves in any way the minus signs could be removed and the prefix im- added to the first word of the quantity represented. The scale, still logarithmic, would then ascend from left to right in the accepted manner and the meaning of the graph become more quickly apparent. As it was, at first sight, it would seem that with a larger ratio of strength to load the risk of failure was actually greater! It would perhaps be as well here to look at one of the figures in everyday terms to see what the risk was really like. A probability of 10^{-8} or, as it might be phrased, an improbability of 10^{8} meant that the chances of failure were one hundred-million to one against.

Elsewhere in the paper was a comparison between the public reactions following small and large aircraft accidents. On the very day this paper was read by Professor Pugsley the front-page main headlines in one of the big newspapers were as follows: "3 Saved From Plane in Sea." The aeroplane referred to was one of the smallest. Although structural failure was not the cause of the mishap it showed that as much interest was taken by some people in small aircraft accidents as in large. It also indicated that such accidents were yet rare enough to make important news items. The national press, he thought, could help to put over a clear picture of the situation if it published comparative accident figures, every quarter say, for all forms of mechanical transport. Also a few other statistics might be given, for example, passenger-miles covered, numbers of vehicles, aircraft or ships in operation, number of long-distance journeys made and so on. Let the public see figures at present only to be found in official documents and it would then be in a position to judge for itself.

Of more concern to the man-in-the-street than structural failure was whether an aeroplane was going to crash. This was probably justified by the fact that pure structural failure had accounted for only a small part of the total number of aircraft disasters. It was just as important, therefore, to give as much consideration to other safety aspects as to purely structural ones. Crashing could be allowed for to a certain extent. The question of rearward facing seats and adequate body support then arose. Elimination of fire risk must also be given much thought. Too much money, skill and time should not be spent on structural calculations and proving tests at the expense of these and other factors. If doubt existed in a particular stressing case, to err slightly on the safe side was unlikely to ruin the economic prospects. As far as the safety in flight of the whole aeroplane was concerned, he agreed with Mr. B. O. Heath that aerodynamics and aeroelasticity should have prime consideration. The provision and perfection of navigational and safe-landing devices should be treated with equal importance. To be structurally safe was in itself far from being completely safe.

In the equations and formulae quoted in connection with Freudenthal's work there was no distinct time factor. This might be the missing link in combining the economic and human elements. Following up the example pertaining to equation (7), they had a structure with a service life of 100 years. It was found to be the most economical if this structure were designed so that if 9,000 were built one would fail during its lifetime. It might be that there was a definite relationship between the number of failures and the physical life of each of them. For instance, it might be a combination of geometric progressions so that out of 15 times the quantity given, *i.e.* 135,000, it could be expected that one would fail in the first fifty years, two between fifty and seventy-five years, four between seventy-five and eighty-seven and a half years and eight during the last twelve and a half years. It was more likely, he thought, that the risk of failure varied in some exponential manner with time but the foregoing was given as a simple numerical example to illustrate the meaning.

In any case, if a definite mathematical relationship were found to exist then the problem was made clearer. The technique then would be to start with a certain life and estimate the probability of failure of the most economic structure: From the rate of failure of this structure and assuming a certain reasonable human risk find the proportion of the life which could be considered the safe life: Then investigate the economics of the

shortened life. Taking several original values the best combination could be found. Aircraft designers could then talk of structural safety and mean it.

IAN TAIG (English Electric Co., Ltd.) *contributed*: He would like to amplify a point already raised in connection with thermal stresses. He would suggest that thermal stresses would play a less important part in the design of safe structures for flight under high temperature conditions than the effects of such temperatures on the mechanical properties of the materials employed. At the present time the thermal problem could only be associated with high speed military aircraft and this would probably be the case for many years to come. These aircraft were usually designed for a comparatively short life and to very high performance factors. Consequently, the number of occasions on which the ultimate design conditions were approached was small.

Professor Pugsley referred to the work of Parkes, which showed that thermal stresses above the elastic limit could cause, in conjunction with flight loads, two types of progressive deterioration, namely:—alternating plastic deformation which could be regarded as a form of fatigue and incremental collapse, or progressive permanent distortion. For these to be catastrophic, it would be necessary for a considerable number of cycles of the design load and temperature conditions to occur in the life of a particular aircraft. Further, it was possible by careful structural design to reduce thermal stresses in the regions subjected to the highest flight loads, and it should certainly be possible to keep these stresses below the elastic limit in the areas affected. If this were done, then the structure would settle down to a fairly normal elastic behaviour after several cycles of load and temperature, as Professor Pugsley stated.

There were no such reassuring thoughts, however, when the effect of high temperatures on the mechanical properties of structural materials was considered. A total exposure time of an hour or less might be sufficient to reduce the material properties to dangerously low values. If the material had been heat-treated to achieve high strength, as with aluminium alloys, then some loss of properties was permanent, when the temperatures had returned to normal. After longer heating times the effect of creep became apparent, although if this only occurred locally it need not have a very serious effect—it might even prove beneficial in relieving stress concentrations. Material selection could go some distance towards solving these problems, but if they had to deal with temperatures above 300° C., then the reduction in material properties made the structural design problem really acute, and these factors must surely outweigh the effects of thermal stresses as such.

The fact that for high temperature operation they must design structures on the basis of reduced material properties obviously entailed a considerable structural weight penalty. To increase structural safety by increasing load factors, as suggested by Professor Pugsley, added further to this weight problem and to the performance limitations which must ensue. In military aircraft the reduction in performance might have more bearing on safety than the increase in structural strength and the proposed solution thus seemed undesirable. It might even be argued that there was a strong case for reducing load factors, but they could see from the paper that such a course would need to be accompanied by a reduction in the adverse scatter of material properties, predicted strengths and predicted loads if the accident rate were not to suffer seriously.

In the technical field this would necessitate more comprehensive aerodynamic, aeroelastic and structural analysis, but with the advent of powerful new computational aids these problems could now be tackled on a scale which could not have been contemplated a few years ago. In any event, the aim of designers and research workers should surely be to use all the means at their disposal to improve the accuracy of their assessment of working loads and strengths, rather than add to the increasingly difficult design problems by raising the factors which covered present inaccuracies.

The use of higher load factors for civil aircraft might not always have the desired results. Professor Pugsley based his assessment of probability of failure on a time scale for a number of aircraft of a given type. Might it not be more realistic to assess probability on the quantity of traffic handled by a given aircraft type? Increasing the load factor only reduced the probability of structural failure, and at the same time increased the structure weight. This must have repercussions on the payload or range, and if they assumed that this type of aircraft was required to handle a constant amount of traffic then they could only suppose that a greater number of flights would have to be made. Thus the probability of non-structural failures, which must be approximately proportional to the number of flights, would be increased, and eventually a point would be reached where this increase would balance out the decrease in probability of structural failure. Further increase in load factor would then be detrimental. As an illustration they could work to the upper curve of Fig. 6. Suppose that the probability of non-structural accidents were six times as great as that of structural failure, then for typical aircraft proportions the maximum desirable load factor was about 2·0.

It would appear that if they could find a convenient means of expressing the probability of non-structural failure, then it should be possible to derive an optimum load factor to minimise the risk of any type of failure. Professor Pugsley's rational approach was capable of extensive development and must ultimately lead to a greater understanding and control of the factors affecting structural safety.

S. WALMSLEY (English Electric Co. Ltd.) *contributed*: Professor Pugsley had dealt with the difficulties encountered in obtaining structural safety. What remained to be seen was how the Aircraft Industry would overcome the difficulties in the future.

A pressing problem seemed to be the scatter of fatigue test results. More work seemed to be required along three main lines.

(*i*) Effect of closer metallurgical control;

(*ii*) Control of surface finish;
(*iii*) Knowledge of the internal stress system of the specimens tested.

Fatigue strength could possibly be raised by applying known self-equilibrating internal stress systems to members. For example, if deformed but relatively stress-free specimens were straightened by applying combined tension and bending so as to leave residual internal compressive stresses on the outer fibres of the specimen, then perhaps an increase in fatigue strength might result, for bending.

Another difficulty of the future was temperature stresses. The effect of temperature gradients would appear to be the most difficult to deal with. The effect of temperature gradients might be reduced by matching materials to temperature. Fortunately materials like titanium and steel which had relatively high strength with temperature, also had relatively low coefficients of thermal expansion. Hence they might conceivably build up composite structures of titanium in high temperature zones attached to aluminium in low temperature zones and separated by a layer of low conductivity, anti-corrosive material.

Creep problems were closely related to temperature problems. Creep possessed the advantage of relieving a structural member of some of its load but the disadvantage of giving a permanent deformation to a structure. The advantages of creep could be artificially induced by pre-stressing members so as to reduce the maximum stresses envisaged.

Finally, more data on flight loads and temperatures was required.

PROFESSOR PUGSLEY'S REPLY

MR. PAGE: He agreed that the relation of the internal stress, due to 100°C temperature rise, to the proof stress was a relevant factor, and that on this basis titanium showed up to advantage. Production costs and difficulties, however, might for long prohibit the general use of titanium; meanwhile steel would seem the best with which to replace aluminium alloys for very high speed aircraft.

He had read something of Hanstock's work at High Duty Alloys and was impressed with its approach and its results. Its concentration on the part played by precipitation at crystal boundaries during fatigue was most interesting and reminded one of the apparently unrelated interest of metal physicists in the movement of dislocations towards crystal boundaries. He felt sure that Hanstock's work was a valuable contribution and looked forward to seeing how it added to the general picture.

Mr. Page had referred to the need for a simpler mode of control of airworthiness. He was not now at all responsible for airworthiness requirements, but he was reminded of an approach that he and some others favoured before the war that aimed at extreme simplicity. There was then no I.C.A.O., but there was an international agreement with America on airworthiness requirements. Just before the 1939-45 War this agreement was due for revision and at the time both sides were newly interested and enthusiastic about the study of accident probabilities. A proposed basis for a new agreement thus arose which centred on an international system for recording and publishing all civil accidents. The idea was that, observing these records and the differences between them in different countries, public opinion would force governments to overhaul their airworthiness standards so as to produce comparable (and low) accident rates in all countries. Thus the essential aim of international airworthiness requirements would be met without any such coming into being! So all the trials and labour of I.C.A.O., it was hoped, might be avoided.

He would just refer to an earlier point made regarding the large volume of *ad hoc* testing work now usual. He was naturally concerned about the need for more fundamental work, both theoretical and experimental. This should help to reduce the *ad hoc* work necessary and, if it could precede rather than follow application, should minimise accidents. Military necessity operated against this, but he hoped that, in the thermal field at least, fundamental work might be in the van as it had often been in the aeroelastic field.

MR. HEATH: First, the magnitude of the work involved in analysing the effects of thermal cycles on a structure. This problem introduced time into structural analysis in a new way, but it was not new to all branches of engineering. To his mind, the problem was comparable to that arising in soil mechanics when the prediction of building settlements and the like were involved. Soil mechanics and aeronautics met on aerodrome runways. Here it was natural that, in the first instance, research workers should discuss the effects of cycles of loading and of thermal cycles on concrete slabs. With the resulting understanding of the problem, however, it was reasonable for the designer to concentrate on the two ends of the picture—the initial and final conditions of support given by the soil to the slab. Such an approach could lead to two rather than twenty sets of design calculations. What the soil mechanics man was becoming accustomed to, the thermal stress man, he thought, could reasonably hope for.

Of importance to any consideration of accident rates was the way in which a structure failed, and he ought perhaps to have made some reference to this in the paper. Aeronautical engineers had become too accustomed to structures which could be intact at one moment and catastrophically damaged the next. They were liable to overlook the traditional desire of engineers for structures that would show warning signs prior to collapse, as by cracking or by plastic deformation. With very high speeds, designers would tend in the future to use steel, and in this he saw hope of a return to the non-catastrophic type of structure. Any move towards redundancy and towards the use of materials and conditions in which cracks were unlikely to spread suddenly—a move likely to arise from fatigue considerations — would have the same general effect.

He was sure that this was an ideal towards which aeronautical engineers should struggle.

MR. KING: He was impressed by the emphasis on structural testing. He had himself sometimes tried to help in the development and provision of structural testing equipment, but the curious thing was that whereas an aerodynamicist would ask for a very large wind tunnel and get it, the structural engineer would ask for a small testing machine and often not get it. Cynics among structural engineers had sometimes felt that the right thing to do was to "cash in" after a major accident. In effect, perhaps, this was what Mr. King was proposing. In the aeroplane field, there was no doubt that new structural testing equipment was needed, but he was not at all certain of the way in which high speed developments would affect this. As soon as one passed from manned aeroplanes to unmanned vehicles, such as rockets and guided missiles, structural safety became, as was said earlier in the discussion, a matter of economics, military or civil. Missile designers were prepared to run risks, and rightly so, and could thus learn more rapidly by experience than could aeroplane designers. This might naturally cause the postponement of investments in large equipment. If Mr. King were to have the very large apparatus he envisaged, he must have it pretty quickly!

MR. LOVELESS: Mr. Loveless had drawn attention to the range of loading conditions to be considered; he agreed with the emphasis on the continued importance of collecting statistical data upon which to base these design conditions.

MR. RHODES: As regards the point about the effects of scatter, either in loads or material properties, upon the load factor required for a given accident rate, he referred to Fig. 6, which was plotted to illustrate a region roughly appropriate to aeronautical conditions. By varying the two types of scatter concerned, both relatively and absolutely, the picture could be materially altered; such changes merited further examination in relation to particular possibilities both in the aeronautical and other fields.

MR. DONKIN: He was interested in the emphasis on the scatter of fatigue test results and the use of a stress factor as a practical measure in this connection. This had earlier been advocated by Dr. Walker and was recently put forward again by Professor Duncan. What was really needed, he felt, was a more informative type of *S-N* diagram, giving not one curve, but several, each corresponding to a definite frequency of occurrence. This would in effect replace the *S-N* diagram with a three-dimensional picture with contours of fixed probability, the type of diagram called by Freudenthal an *S-N-P* diagram. It would be very useful if the extensive fatigue testing required to provide the necessary data could be done on even a few typical structural specimens. With such diagrams as a guide, a clearer and perhaps new view of the scatter problem would arise.

MR. GILL: The references to the relevance of the ratio of ultimate to proof load for a structure reminded him of the "Report on Structural Safety" just prepared by the Institution of Structural Engineers, where some emphasis was placed on the value of warning signs in a structure when loaded between these two limits. As to insurance rates, although of interest and of relevance, he would point out that such rates commonly covered many other risks of failure as well as those associated with structural collapse, and it was not often that rates for the latter could be distinguished.

MR. HUGHES: He agreed that Mr. Hughes' proposal for replacing a discussion of risks with one on chances of success would probably be more popular for general consumption and for issue by aeroplane operators, but he was sure that designers and research workers would always be more concerned about accidents than about safe journeys. He agreed that structural accidents were in the minority and work on other types of accident was very important.

MR. TAY AND MR. WALMSLEY: He agreed too with the general points made. He was interested in Mr. Tay's proposal to analyse accidents in terms of a given traffic, but realised that, for wide variations, the one was a function of the other, which would complicate matters. Exploratory work along this and other lines, however, would be all to the good.

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

A Possible Method of Impedance Testing Aircraft Power Control Units

by

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(*Handley Page Ltd.*)

KNOWLEDGE of the motions of aircraft control surfaces due to oscillating hinge moments is of great importance for flutter investigations. While the impedance of the power control unit may play a large part in determining these motions, it is not their only cause. The elasticity of the power unit mounting and the effect on the input of distortion of the aircraft structure, an effect which may depend on air speed, may also be important. Nevertheless the influence of the power unit itself is of major importance. No very satisfactory methods appear to have been devised yet, however, for making such tests. The difficulty lies chiefly in applying the large oscillatory loads to the output of the power control unit, which are necessary if the test is to be realistic. The facts that the oscillating loads must be applied to the jack while it is moving, and that a non-oscillatory opposing load is also desirable, add to the difficulties. For convenience in assessing the characteristics of the unit, it is desirable that the oscillating load should be superimposed on a constant opposing load and that the basic jack motion should be of constant velocity.

One method which has been used is to attach the jack to a mechanical exciter, supported vertically, but free to move horizontally. Oscillating loads are applied to the jack by the exciter which is essentially an oscillating mass, the constant opposing load being applied by hydraulic jacks or other means. This method runs into difficulties at the lower end of the required frequency range, however, because of the very large oscillating mass required. Other methods suggested are due to Watson[1] and Hadekel[2]. The method to be outlined here, which has not yet been applied in practice, appears to be relatively simple and to have certain advantages over previous methods.

1. DESCRIPTION OF PROPOSED METHOD

The method proposed entails the use of two separate power units, one to apply the loads to the other. The two units *A* and *B* are mounted as shown in Fig. 1 with the two output jacks connected by means of a very stiff spring. The input levers to the two units are interconnected by means of a differential linkage, as shown in Fig. 2. The actuator *C* gives the constant velocity input to both the power units. The sinusoidal oscillator *D* causes the input to unit *B* to have superimposed upon it a small amplitude oscillation. This causes the jack motion of unit *B* to be of a similar nature. This discrepancy between the motion of the two jacks causes oscillating loads to be imposed on both jacks due to the stiff spring connecting them. To obtain a steady jack load in addition, a constant displacement of the two jacks relative to each other is required. This can be introduced by displacing the point *E* of the differential linkage in Fig. 2.

The constant part of the load in the spring causes work to be done by one unit and to be absorbed by the other when the jacks are in motion. This load can of course be made to oppose or assist the jack of unit *A*, the unit to be tested.

2. DISCUSSION OF METHOD

It is not necessary that the two units used in the test be identical, although it is desirable that the unit used to apply the loads should be of as high a load capacity as the unit to be tested. An advantage of the method is that if the units are mounted as in Fig. 1, the jack loads are balanced so that no loads are transmitted outside the rig, and a very simple and compact rig can be used.

Because of the frequency response characteristics of the power control unit, the amplitude of oscillation of the output jack is attenuated relative to the input, especially at the higher frequencies. Most hydraulic servos, however, have sufficient response at the frequencies concerned to apply the loads required. For units having valves with overlap, the attenuation of the oscillation when the jack is moving will be less than that obtained during frequency response tests at zero rate. A preliminary test would be necessary to determine approximately, for a given rate, the amplitude of the input oscillation required to give the desired amplitude of jack load. During the actual test the motion of both jacks under the oscillating load would affect the loads obtained.

The valve opening required for a given rate of jack movement usually depends on the jack load. During the test the constant parts of the loads applied to the two

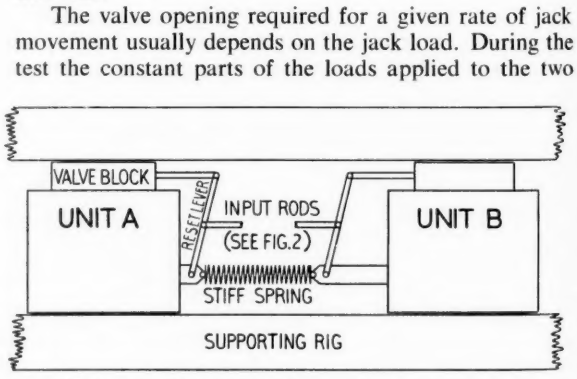

FIGURE 1. The power unit mounting arrangement.

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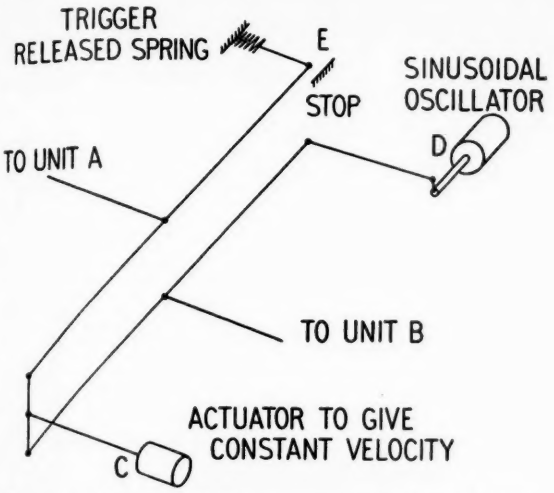

FIGURE 2. Diagram showing interconnection of input linkages.

units will be of opposite sign so that the valve opening required will be different in the two cases. The relative displacement of the two jacks, and consequently the steady load, for a given constant displacement of the input point E in Fig. 2, will therefore be affected by the rate of movement. Since the spring between the jacks must be of high stiffness, it is essential that the constant input displacement should be applied while the jacks are moving, as to do so before motion starts would entail very high initial loads which would then fall off as the jacks began to move. To determine the jack load corresponding to a given input displacement again calls for a preliminary run. In order to make the input displacement, a trigger-released, pre-loaded spring strut arrangement is suggested.

The sequence of operations envisaged is:

(*i*) set jacks at one end of their travel with zero load in the spring.
(*ii*) start oscillator.
(*iii*) start constant velocity actuator.
(*iv*) trigger off small displacement.

3. LIMITATION DUE TO VALVE OVERLAP

The non-linearities in the valve characteristics are unlikely to cause the output motion to differ seriously from sinusoidal, so long as the valve does not move to within its overlap, *i.e.* so long as the rate of jack motion does not actually reverse. This limits the amplitude of the oscillatory part of the motion. A stiff spring is therefore required to obtain the required amplitude of jack load.

If the constant rate of jack movement is $\dot{x}$ and the amplitude of oscillation A at circular frequency ω (rads./sec.) then, to ensure that the velocity does not reverse, we must have $A\omega < \dot{x}$.

If the spring stiffness is C then the jack load amplitude is obviously AC.

To illustrate this limitation, an impedance test on a power unit of maximum load, of say 10,000 lb., and maximum rate, of say, 10 in./sec. will be considered. The maximum amplitude of load to be applied will be taken as $\pm$ 2,000 lb. and it will be assumed that the lowest rate at which the test is to be done is one in./sec. If the upper frequency to be considered is 20 c.p.s. then the maximum amplitude which can be tolerated at one in./sec. is $A = \dot{x}/\omega = 1/(20 \times 2\pi) = \pm 0{\cdot}008$ in. and a spring stiffness of 250,000 lb./in. is required to obtain a load amplitude of $\pm$ 2,000 lb. A jack amplitude of $\pm 0{\cdot}008$ in. is probably the smallest that can be measured with reasonable accuracy. Clearly the frequency range could be extended upwards at higher steady rates, and lower rates could be dealt with over a reduced frequency range.

Making a spring of the stiffness indicated and of adequate strength should not present any insuperable difficulty. The same spring could be used for tests over the complete frequency range at constant load amplitude, although it would obviously be desirable to use a softer spring with consequent larger displacements at the lower frequencies.

4. QUANTITIES TO BE MEASURED

4.1. Jack Load

As pointed out in Section 2 the load applied to the jacks is itself affected by the impedance of the units. The load must therefore be measured directly. The complete time history of the load in the spring is required. This can be obtained either by means of a strain gauge or by direct measurement of the displacement of the jacks relative to each other. The measurement must be accurate enough to enable the phasing of the oscillatory part of the load to be determined.

4.2. Jack Motion

Ideally, the complete time history is required of the jack displacement relative to space, it being assumed that there is no bodily displacement of the power units due to the mounting. Unfortunately, since the amplitude of any oscillation will be small in relation to the total jack travel, measurements of this kind, accurate enough to give the amplitude and phase of the oscillation, are difficult to make. This, of course, is the case whatever method of testing is adopted. As a substitute for these measurements, the displacement of the valve will yield the oscillations of the jack end of the reset lever, since this lever is rigid and the input is of known constant velocity. The oscillations of the jack end of the reset lever will give the oscillations of the jack output, provided that the unit is rigidly mounted and, in the general case, that there is no distortion of the body of the power unit. In the particular case of a power unit as drawn in Fig. 1, in which the reset lever is connected directly to the jack output, then the valve displacement will give the motion of the jack output including the effects of any distortion of the jack housing.

As an alternative to measurements of displacement, measurements of the jack acceleration could be made.

1. WATSON, C. D. (1953). Variable Hydraulic Pump Servos, and a Method of Impedance Testing. *Conference on Hydraulic Servo Mechanisms.* Institution of Mechanical Engineers Proceedings. 1953.
2. HADEKEL, R. (1954). Some Problems of Powered Flying Controls. M.O.S. S. & T. Memo. No. 2/54. 1954.

A Note on the Excitation of Vibrating Systems by Gearing Errors

by

D. C. JOHNSON AND R. E. D. BISHOP

IN A RECENT paper[1], Yates has shown that it is convenient to distinguish between *two* main types of stimulus which induce torsional vibration in geared-shaft systems. The first, which is dealt with in detail in the literature, is "force excitation" by which periodic torques act upon the system and throw it into oscillation; for the purpose of this note, it will be convenient to refer to a previous article[2] as dealing with this problem.

The second type of excitation to which Yates refers is "displacement excitation." It may be thought of as arising from errors in the cutting of gears which cause periodic variations in the velocity ratio of mating components. A Hooke's joint which couples two rotating systems which are capable of torsional oscillation would give rise to this form of stimulus.

The purpose of this note is to discuss this second type of excitation by the use of receptances[2]. It is found that these functions provide a ready means of examining problems in which either sort of excitation exists.

It will be convenient to use the same notation as before[2], except that, here, the well-known complex representation of harmonically varying quantities will be used (*e.g. see* Ref. 3). Once more, the effects of (linear) damping will be disregarded in the interests of simplicity; this is by no means essential to the theory which holds good whether the system is conservative or not. The effect of damping is to make the receptances complex[3].

EXCITATION AT THE GEARING OF A SIMPLE SYSTEM

Figure 1 represents a composite system composed of sub-systems *B* and *C* which are linked through a gear whose ratio is, nominally, $n : 1$. For the separate systems,

$$\left.\begin{aligned} x_1 &= X_1 e^{i\omega t} = \beta_{11} F_1 e^{i\omega t} \\ x_2 &= X_2 e^{i\omega t} = \gamma_{22} F_2 e^{i\omega t} \end{aligned}\right\} \quad . \quad (1)^*$$

Suppose that there is a gearing error such that the compatibility condition at the junction of the sub-systems *B* and *C* is

$$x_2 = n x_1 + E e^{i\omega t} \quad . \quad . \quad . \quad (2)$$

where $E \ll n x_1$ and where ω will generally be a multiple of the speed of one of the shafts in radians per second. This equation may be written in the form

$$X_2 = n X_1 + E. \quad . \quad . \quad . \quad (3)$$

*This notation differs slightly from that used in entry 3 of Table II of Ref. 2. The difference arises because it is convenient here to assign different symbols (x_1 and x_2) to the displacements of *B* and *C*. This should not cause difficulty; equations (1) follow from the definition of a receptance.

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The condition of equilibrium between *B* and *C* is

$$F_1 \times 1 + F_2 \times n = 0 \quad . \quad . \quad . \quad (4)$$

if it be assumed that there is no "force excitation" at the junction.

The conditions (3) and (4), when they are imposed upon equations (1), lead to the following results

$$x_1 = X_1 e^{i\omega t} = -\frac{n\beta_{11} E e^{i\omega t}}{\gamma_{22} + n^2 \beta_{11}} \quad . \quad . \quad (5)$$

$$x_2 = X_2 e^{i\omega t} = \frac{\gamma_{22} E e^{i\omega t}}{\gamma_{22} + n^2 \beta_{11}}. \quad . \quad (6)$$

These are the responses at the junction of the two systems *B* and *C* expressed in terms of their receptances.

The condition of resonance is

$$\gamma_{22} + n^2 \beta_{11} = 0 \quad . \quad . \quad . \quad (7)$$

and this may be shown to be the resonance condition for "force excitation" (*see* Ref. 2). In fact, (7) is the frequency equation of the composite system with no gearing error.

CONCLUSION

The excitation of vibrating systems by applied harmonic forces may be treated in a straightforward manner by consideration of receptances (*e.g. see* Ref. 2). It is shown here that "displacement excitation," in which vibration is caused by relative displacements arising in gear mesh, may also be dealt with in this way.

The phenomenon of displacement excitation is discussed by Yates[1] who states that "the simplest and most usual cause is a slight eccentricity in a pinion, which entails relative advancement and retardation of simple harmonic character between pinion and gear wheel, performing a complete cycle in one revolution of the pinion. Eccentricity of less than one thousandth of an inch may cause heavy vibration torques . . . but by

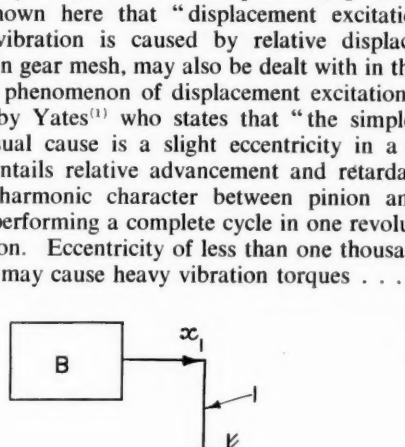

FIGURE 1.

proper design these torques may be greatly reduced even with appreciable errors."

While the theory has been developed only for the particular system of Fig. 1, the method may easily be applied to more complicated problems, with or without damping.

REFERENCES

1. YATES, H. G. (1955). Prediction and Measurement of Vibration in Marine Geared-Shaft Systems. Paper presented to the Institution of Mechanical Engineers, April 1955.
2. BISHOP, R. E. D. (1954). The Analysis and Synthesis of Vibrating Systems. *Journal of the Royal Aeronautical Society*, October 1954.
3. DUNCAN, W. J. (1947). Mechanical Admittances and their Applications to Oscillation Problems. R. & M. 2000, 1947.

Effect of Variations in Weight or Normal Acceleration on the Ceiling of Jet-Propelled Aircraft

by

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(A. V. Roe and Co. Ltd.)

THE ABILITY to manoeuvre at high altitude has become one of the main requirements in the design of modern military aircraft. Ability to manoeuvre enables the fighter pilot to execute tight turns during the attack on a bomber and the bomber pilot to perform evasive manoeuvres and so make the task of the fighter more difficult.

Normally the main manoeuvre considered is the application of increased normal acceleration, or g, and if we assume that (*a*) there is sufficient pitching power available from the longitudinal control surface to increase the wing incidence to give the necessary increase in normal force, and (*b*) that the new wing incidence is below the stalling incidence of the wing, then the degree of manoeuvrability available is a function of thrust and drag alone. In the past the manoeuvrability required at a given altitude has been expressed in terms of the rate of climb available at that altitude and thus we have such definitions as "the 1,000 ft./min. ceiling" and so on. The derivation of the actual manoeuvrability, in terms of increased normal acceleration available at altitude, from this definition is then dependent upon the operating speed and the drag characteristics of the aircraft.

Recently it has become more common practice to specify the manoeuvrability requirements directly in terms of the amount of normal acceleration that can be applied to the aircraft without losing altitude. The main advantage of the new definition is that it enables two aircraft to be compared much more directly, only the respective true air speeds being required to evaluate their minimum turning radii at any specified altitude.

The effect of increased normal acceleration on the drag of an aircraft at constant air speed is identical to that due to an increase in weight; for instance, the drag increase in a $2g$ turn at constant altitude is equal to the drag increase in $1g$ flight due to doubling the weight of the aircraft at the same air speed and height.

If the simple equations of thrust and drag during steady flight are considered, it can be shown that the *change in maximum altitude* at a given Mach number and engine setting, due to a change in normal acceleration or weight is *the same for any jet-propelled aircraft* flying in the stratosphere. This identity is completely independent of the size of the aircraft, its shape, drag, engine thrust or actual flight speed, providing the changes in altitude take place in an isothermal atmosphere.

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This is, at first sight, a remarkable generalisation but it is easily shown as follows:

The drag of an aircraft in longitudinally unaccelerated flight at constant altitude is equal to the net thrust available from the engines and the equality can be written simply as:

$$T=D=(C_D/C_L)\times nW \quad . \quad . \quad (1)$$

where

T thrust (lb.)
D drag (lb.)
C_D drag coefficient $= \dfrac{D}{\frac{1}{2}\rho_0\sigma V_T^2 S}$
C_L lift coefficient $\simeq \dfrac{nW}{\frac{1}{2}\rho_0\sigma V_T^2 S}$
n normal acceleration factor
W aircraft weight (lb.)
ρ_0 density of atmosphere at sea level (slugs/ft.^{3})
σ relative density
V_T true air speed (ft./sec.)
S wing area (ft.^{2}).

Now it can be shown, theoretically, that the net thrust of a jet engine can be expressed as:

$$T/p=f_1\left(\frac{N}{\sqrt{\theta}}\ ,\ \frac{V_T}{\sqrt{\theta}}\right)$$

where

p ambient static pressure (lb./ft.^{2})
N engine speed (r.p.m.)
θ ambient absolute temperature (°K.),

and this expression can be re-written as

$$T/p=f_2\left(\frac{N}{\sqrt{\theta}}\ ,\ M\right)$$

where M is the Mach number.

In an isothermal atmosphere p/ρ is constant. Thus:

$$T/\rho=f_3\left(\frac{N}{\sqrt{\theta}}\ ,\ M\right)$$

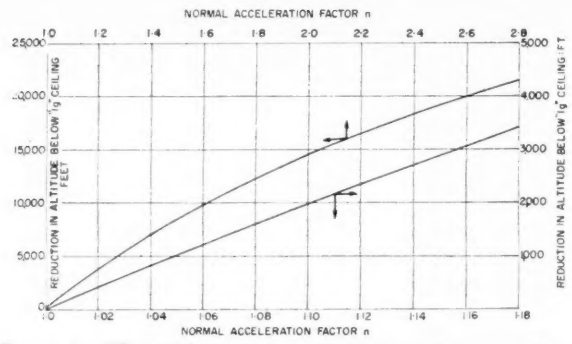

FIGURE 1. Effect of increase in normal acceleration on ceiling at constant Mach number and engine setting.

and as the value of θ is constant in the isothermal atmosphere, then for a constant engine r.p.m., N, and Mach number M:—

$$(T/\sigma)_{M,N,\theta} = \text{constant} \quad . \quad . \quad (2)$$

provided that the effects of changes in Reynolds number due to changes in altitude can be ignored.

Also from equation (1)

$$T/\sigma = (C_D/C_L) \times nW/\sigma \quad . \quad . \quad (3)$$

Now for any given aircraft/engine combination the ratio of drag coefficient to lift coefficient for maximum altitude flight is constant at a given Mach number, again on the assumption that Reynolds number effects can be ignored, and thus equation (3) simplifies to

$$(nW/\sigma)_{M,N,\theta} = \text{constant} \quad . \quad . \quad (4)$$

Considering the effect of changes in either n, or W, or both, on the maximum altitude for a given engine setting and flight Mach number equation (4) becomes:—

$$\left(\frac{n_1 W_1}{n_2 W_2}\right) = \sigma_1/\sigma_2 \quad . \quad . \quad . \quad (5)$$

and this expression is *quite independent of the shape of the aircraft, the thrust of its engines, its maximum altitude at a given value of n and W, or its flight Mach number*, provided that the changes in altitude are

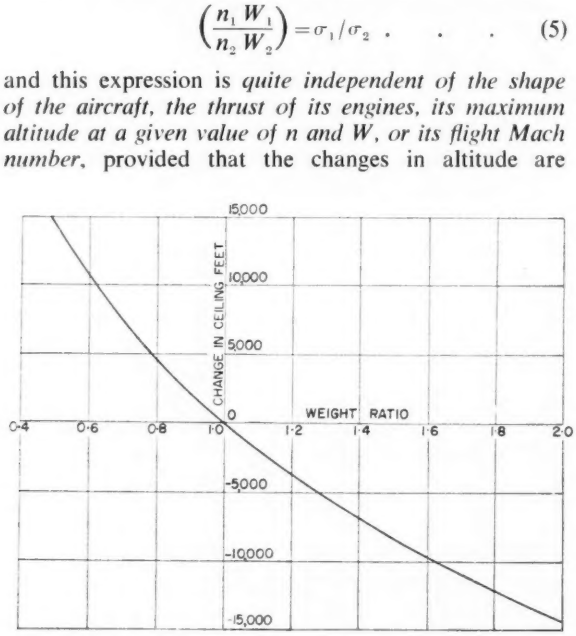

FIGURE 2. Effect of proportionate change in weight on ceiling at constant Mach number and engine setting.

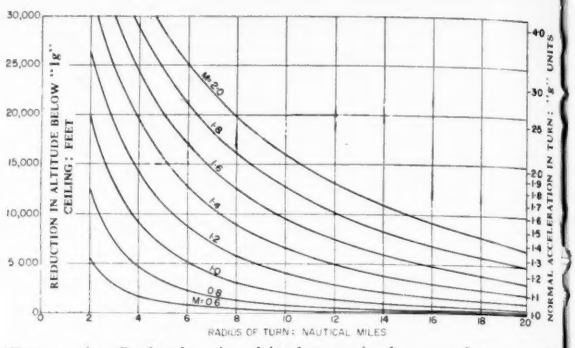

FIGURE 3. Reduction in altitude required to perform steady turns at constant Mach number and engine setting.

assumed to take place at constant Mach number and engine setting in an isothermal atmosphere.

It will be noted that the only assumption in the above analysis is that the change in Reynolds number associated with the change in height at constant Mach number does not affect the drag of the aircraft nor the T/σ relationship. This is not true for large variations in height but should be insignificant for altitude changes of the order considered here.

Normally the stratosphere is regarded as an isothermal atmosphere and consequently the relation between height and density in the stratosphere is given simply by

$$h_1 - h_2 = B\theta \log_e (\sigma_2/\sigma_1) \quad . \quad . \quad (6)$$

where B gas constant = 96 ft./°C.

and σ_1, σ_2 relative density at heights h_1 and h_2 respectively.

Substituting equation (5) into equation (6)

$$h_1 - h_2 = B\theta \log_e \left(\frac{n_2 W_2}{n_1 W_1}\right) \text{ feet}$$

and substituting the numerical values of B and θ

$$h_1 - h_2 = 20{,}784 \log_e \left(\frac{n_2 W_2}{n_1 W_1}\right) \text{ feet} \quad . \quad (7)$$

From this equation it is seen that the actual *change in height* in feet, due to changes in normal acceleration and/or proportionate changes in weight, is independent of the aircraft and its flight Mach number with the same provisos as before.

It is now possible to produce unique curves from (7) for the following variations:

(*a*) The effect of change in normal acceleration at constant weight.
(*b*) The effect of change in weight in 1*g* flight.
(*c*) The reduction in height below the 1*g* ceiling required to achieve a given radius of turn, in level flight.

These three relationships are shown in Figs. 1, 2 and 3 respectively and the following interesting observations are possible.

On the assumptions of flight in the stratosphere at constant Mach number and engine setting (but not necessarily the same Mach number and engine setting

for each aircraft) the reduction in height below the 1g ceiling required to achieve a 1·2g turn is 3,700 ft. (Fig. 1). Similarly the effect of a 50 per cent. increase in weight is to reduce the 1g ceiling by about 8,400 ft. irrespective of the aircraft, its ceiling at a given weight, or its flight Mach number (Fig. 2). Furthermore, the reduction in height below the 1g ceiling required to perform a turn of 10 nautical miles radius is 800 ft. at a Mach number of 0·8 and is 16,000 ft. at a Mach number of 2·0 (Fig. 3).

The implications of these unique values in terms of the ability of the jet fighter to attack the jet bomber are also interesting. It is seen that if the fighter is to attack the bomber at the 1g ceiling altitude of the latter and have a manoeuvrability of, say, 2g in steady level flight at that altitude, then the 1g ceiling of the fighter at its attack Mach number and engine setting must be some 14,500 ft. higher than that of the bomber at the bomber's own cruise Mach number.

The overall problem of interception and attack is, of course, more complex than this, but it indicates that the bomber's best defence lies in its absolute altitude or 1g ceiling. The differences between the altitude requirements of the bomber and fighter may not be so large as suggested above, but here again it is clear that the task of producing a pure-jet fighter capable of attacking a contemporary pure-jet bomber with any reasonable chance of success is far from easy.

The difficulty of maintaining the superiority of the fighter increases with increase in the cruising altitude of the bomber and this superiority may only be restored in future designs by the use of some other type of power plant, such as the rocket motor, which is not limited by the (T/σ) law. For instance, a rocket motor could be used as a "booster" on a jet fighter to obtain large increases in thrust at high altitude during the combat period.

ACKNOWLEDGMENTS

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The Influence of Body Forces on the Stability of a Reinforced Rectangular Plate

by

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REINFORCED rectangular plates find frequent application in the field of aeroplane structures, ship structures and allied fields. The stability of a structural element, if its critical load in compression is rather low, is normally influenced by its own weight. Usually the ratio of the body forces of the stiffened plate to the critical load is a considerable amount and the influence of the body forces of the plate and the ribs on the critical load of the stiffened plate is discussed here.

In this note (following Timoshenko), the extensional deformation of the middle surface during buckling is neglected, which greatly simplifies the analysis. Although it leads to an under-estimation of the critical load (of the order of 10 per cent at most) it is not likely to influence the general conclusions. Strain energy method of analysis is used.

Further, nomograms are constructed, which should be useful in design offices where sheet-stiffener combinations are used.

NOTATION

w	displacement in z direction
x, y, z	Cartesian co-ordinates
σ_{cr}	critical stress
a, b	plate dimensions
B	flexural rigidity of rib $= EI$
D	flexural stiffness of plate per unit width $= Eh^3/\{12(1-\nu^2)\}$
P_i	axial load on the i^{th} rib
A_i	cross-sectional area of the i^{th} rib
N_y	compressive load per unit width of the plate in the y direction including its own body force
h	thickness of plate
γ'	the specific weight
n	number of half waves into which the plate buckles in a direction parallel to y axis
m	number of half waves into which the plate buckles in a direction parallel to x axis

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INTRODUCTION

Greenhill, Jasinsky, Grischoff and Timoshenko[2] have done much work on the influence of their own weight on the buckling of prismatical bars.

Henry Favre[1] considered the influence of its own weight on the stability of a rectangular plate and Timoshenko[2] obtained the expression for the critical load of rectangular plate, reinforced by ribs, neglecting the gravity forces. This note is concerned with the critical load of a reinforced rectangular plate, taking into consideration the body forces; the condition is derived for the critical stress to be high, which may be of some interest to engineers.

As a fundamental case, a rectangular plate reinforced by one rib centrally placed, has been discussed and this can be extended to any number of ribs, equally spaced or otherwise.

ASSUMPTIONS

1. When the plate buckles, the elastic limit is not exceeded.

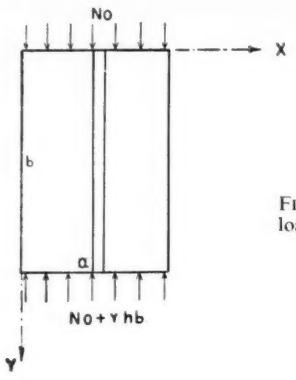

FIGURE 1. Reinforced plate loading and co-ordinate system.

2. The strain energy in torsion of the rib is neglected.

3. The plate and the rib act together as there is a continuous line of connection between the two.

4. The classical small deflection theory is used, *i.e.* the strain energy due to bending is large as compared to that due to stretching of the middle plane of plate ($w \ll h$). This is an artificial assumption introduced to simplify the analysis and does not influence the general conclusions.

STRAIN ENERGY THEORY

Consider a reinforced rectangular plate, simply-supported on all four sides, in longitudinal compression as shown in Fig. 1.

$$\text{Let} \quad w = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \quad . \qquad (1)$$

be the equation of the deflected surface of a rectangular plate, simply-supported on all four edges.

$$N_x = N_{xy} = 0 \qquad N_y = N_0 + \gamma' hy. \quad . \qquad (2)$$

Applying energy methods, the critical load can be obtained by equating the sum of the strain energies of the bending of the plate and the bending of the rib to the work done during buckling by compressive forces, including body forces on the plate and on the rib.

ΔV = strain energy of bending of plate

$$= \frac{D}{2} \int_0^a \int_0^b \left\{ \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right)^2 - 2(1-\nu) \left(\frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} - \left[\frac{\partial^2 w}{\partial x \partial y} \right]^2 \right) \right\} dxdy$$

$$= \frac{\pi^4 ab}{8} D \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^2 a_{mn}^2 \quad . \quad . \qquad (3)$$

ΔV_i = strain energy of bending of rib

$$= \frac{B_i}{2} \int_0^b \left(\frac{\partial^2 w}{\partial y^2} \right)_{x=c_i} dy$$

$$= \frac{\pi^4 B_i}{4b^3} \sum_{n=1}^{\infty} n^4 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2$$

$$. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

ΔT = work done during buckling by compressive forces and body forces on the plate

$$= \frac{1}{2} \int_0^a \int_0^b \left\{ N_x \left(\frac{\partial w}{\partial x} \right)^2 + N_y \left(\frac{\partial w}{\partial y} \right)^2 + 2N_{xy} \frac{\partial w}{\partial x} \frac{\partial w}{\partial y} \right\} dxdy$$

$$= \frac{1}{2} \int_0^a \int_0^b (N_0 + \gamma' hy) \left(\frac{\partial w}{\partial y} \right)^2 dxdy$$

$$= \frac{\pi^2 a}{8b} N_0 \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} n^2 a_{mn}^2 + \frac{\pi^2}{4} \gamma' ha \sum_{m=1}^{\infty} \left\{ \frac{1}{4} \sum_{n=1}^{\infty} n^2 a_{mn}^2 - \frac{4}{\pi^2} \sum_{n=1}^{\infty} \sum_{q=1}^{\infty} \frac{q^2+n^2}{(q^2-n^2)^2} nq a_{mn} a_{mq} \right\} . \qquad (5)$$

n being all integral positive numbers greater than q such that $q \pm n$ is an odd number.

ΔT_i = work done during buckling by compressive forces including body forces on the rib

$$= \int_0^b \left(\frac{P_i + \gamma' Ay}{2} \right) \left(\frac{\partial w}{\partial y} \right)^2_{x=c_i} dy$$

$$= \frac{\pi^2 P_i}{4b} \sum_{n=1}^{\infty} n^2 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2 +$$

$$+ \frac{\pi^2 \gamma' A}{8} \sum_{n=1}^{\infty} n^2 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2 -$$

$$- \gamma' A \sum_{n=1}^{\infty} \sum_{q=1}^{\infty} nq \frac{q^2+n^2}{(q^2-n^2)^2} \left[\left(a_{1n} a_{1q} \sin^2 \frac{\pi c_i}{a} + a_{2n} a_{2q} \sin^2 \frac{2\pi c_i}{a} + \ldots\ldots \right) + \sum_{m=1}^{\infty} \sum_{p=1}^{\infty} a_{mn} a_{pq} \sin \frac{m\pi c_i}{a} \sin \frac{p\pi c_i}{a} \right] . \qquad (6)$$

$m \pm p$ is even and $q \pm n$ is odd.

Equating equations (3) and (4) to (5) and (6).

$$N_0 = \frac{\pi^4 ab}{8} D \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left(\frac{m^2}{a^2} + \frac{n^2}{b^2} \right) a_{mn}^2 +$$

$$+ \frac{\pi^4 B_i}{4b^3} \sum_{n=1}^{\infty} n^4 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2 -$$

$$- \frac{\pi^2}{4} \gamma' ha \sum_{m=1}^{\infty} \left\{ \frac{1}{4} \sum_{n=1}^{\infty} n^2 a_{mn}^2 - \frac{4}{\pi^2} \sum_{n=1}^{\infty} \sum_{q=1}^{\infty} \frac{q^2+n^2}{(q^2-n^2)^2} nq a_{mn} a_{mq} \right\} -$$

$$- \frac{\pi^2 P_i}{4b} \sum_{n=1}^{\infty} n^2 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2 -$$

$$- \frac{\pi^2 \gamma' A}{8} \sum_{n=1}^{\infty} n^2 \left(a_{1n} \sin \frac{\pi c_i}{a} + a_{2n} \sin \frac{2\pi c_i}{a} + \ldots\ldots \right)^2 +$$

$$+\gamma' A \sum_{n=1}^{\infty}\sum_{q=1}^{\infty} nq\frac{q^2+n^2}{(q^2-n^2)^2}\left[\left(a_{1n}a_{1q}\sin^2\frac{\pi c_i}{a}+\right.\right.$$

$$\left.+a_{2n}a_{2q}\sin^2\frac{2\pi c_i}{a}+\ldots\ldots\right)+$$

$$\left.+\sum_{m=1}^{\infty}\sum_{p=1}^{\infty}a_{mn}a_{pq}\sin\frac{m\pi c_i}{a}\sin\frac{p\pi c_i}{a}\right]\div\frac{\pi^2 a}{8b}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}n^2 a_{mn}^2. \quad (7)$$

To simplify, the following notation is introduced:

$$\frac{b}{a}=\beta \text{ aspect ratio} \quad (8)$$

$$\frac{B_i}{aD}=\gamma_i' \text{ flexural stiffness ratio} \quad (9)$$

$$\frac{P_i}{aNy}=\frac{A_i}{ah}=\delta_i \text{ area ratio} \quad (10)$$

$$\xi=\frac{\gamma' hb}{\pi^2 D/b^2} \quad (11)$$

The numerator is the weight of a vertical element of unit width and the denominator is the Euler's load of a vertical element of the same width.

$$N=\frac{\gamma' A_i b/a}{\pi^2 D/b^2} \quad (12)$$

The numerator is the weight of the stiffener, corrected for aspect ratio. The denominator is the same as before.

$$K=\frac{\sigma_{cr}h}{\pi^2 D/a^2} \quad (13)$$

where K is the ratio of the critical load and Euler's load of a horizontal element, both of unit width. Then

$$\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}(m^2\beta^2+n^2)^2 a_{mn}^2+2\gamma_i\sum_{n=1}^{\infty}n^4\left(a_{1n}\sin\frac{\pi c_i}{a}+\right.$$

$$\left.+a_{2n}\sin\frac{2\pi c_i}{a}+\ldots\ldots\right)^2-$$

$$-2\xi\sum_{m=1}^{\infty}\left\{\frac{1}{4}\sum_{n=1}^{\infty}n^2 a_{mn}^2-\frac{4}{\pi^2}\sum_{n=1}^{\infty}\sum_{q=1}^{\infty}\frac{q^2+n^2}{(q^2-n^2)^2}nq\,a_{mn}a_{mq}\right\}-$$

$$-N\sum_{n=1}^{\infty}n^2\left(a_{1n}\sin\frac{\pi c_i}{a}+a_{2n}\sin\frac{2\pi c_i}{a}+\ldots\ldots\right)^2+$$

$$+\frac{N}{\pi^2}\sum_{n=1}^{\infty}\sum_{q=1}^{\infty}\frac{q^2+n^2}{(q^2-n^2)^2}nq\left[\left(a_{1n}a_{1q}\sin^2\frac{\pi c_i}{a}+\right.\right.$$

$$\left.+a_{2n}a_{2q}\sin^2\frac{2\pi c_i}{a}+\ldots\ldots\right)+\sum_{m=1}^{\infty}\sum_{p=1}^{\infty}a_{mn}a_{pq}\sin\frac{m\pi c_i}{a}$$

$$\left.\sin\frac{p\pi c_i}{a}-K\beta^2\left[\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}n^2 a_{mn}^2+\right.\right.$$

$$\left.+2\delta_i\sum_{n=1}^{\infty}n^2\left(a_{1n}\sin\frac{\pi c_i}{a}+a_{2n}\sin\frac{2\pi c_i}{a}+\ldots\ldots\right)^2\right]=0. \quad (14)$$

Equating the derivative of equation (14) with respect to the coefficient a_{mn} the critical buckling value is obtained.

As a fundamental case, let c_i be equal to $a/2$, *i.e.* one rib divides the plate into two equal parts. This can be extended to one or more ribs, spaced equally or otherwise, but the calculations become more elaborate in the latter case.

Without limiting the generality of the conclusions, it can be assumed that the plate buckles into one half wave vertically and since $q\pm n$ is odd, equation (14) reduces to

$$a_m(m^2\beta^2+1)^2+2\gamma(a_1-a_3+a_5-\ldots\ldots)-\frac{\xi}{2}a_m-$$
$$-N(a_1-a_3+a_5-\ldots\ldots)-$$
$$-K\beta^2[a_m+2\delta(a_1-a_3+a_5-\ldots\ldots)]=0. \quad (15)$$

The following new symbols are introduced to simplify this:

$$\left.\begin{aligned}A&=(1+\beta^2)^2+2\gamma-\frac{\xi}{2}-N\\ B&=(1+9\beta^2)^2+2\gamma-\frac{\xi}{2}-N\\ C&=(1+25\beta^2)^2+2\gamma-\frac{\xi}{2}-N\\ D&=(1+49\beta^2)^2+2\gamma-\frac{\xi}{2}-N\\ X&=-2\gamma+N+2K\beta^2\delta.\end{aligned}\right\} \quad (16)$$

First approximation

Only one coefficient $a_1\neq 0$; the others are all zero.

$$K=\frac{(1+\beta^2)^2+2\gamma-\frac{\xi}{2}-N}{\beta^2(1+2\delta)}=\frac{A}{\beta^2(1+2\delta)}. \quad (17)$$

The criterion for the buckling stress to be high is to design the dimensions of the reinforced plate such that

$$2\gamma\gg\frac{\xi}{2}+N.$$

Particular cases are:

(*a*) Buckling stress of a reinforced plate ($N=\xi=0$)

$$K=\frac{(1+\beta^2)^2+2\gamma}{\beta^2(1+2\delta)} \quad (18)$$

which agrees with equation (225) of Ref. 2.

(*b*) Buckling stress of a non-reinforced plate, considering its own weight ($\delta=\gamma=N=0$)

$$K=\frac{(1+\beta^2)^2-\xi/2}{\beta^2} \quad (19)$$

which agrees with equation (12) of Ref. 1.

For higher values of β, the first approximation itself gives accurate results; for smaller values, the second or the third or higher approximations are to be used.

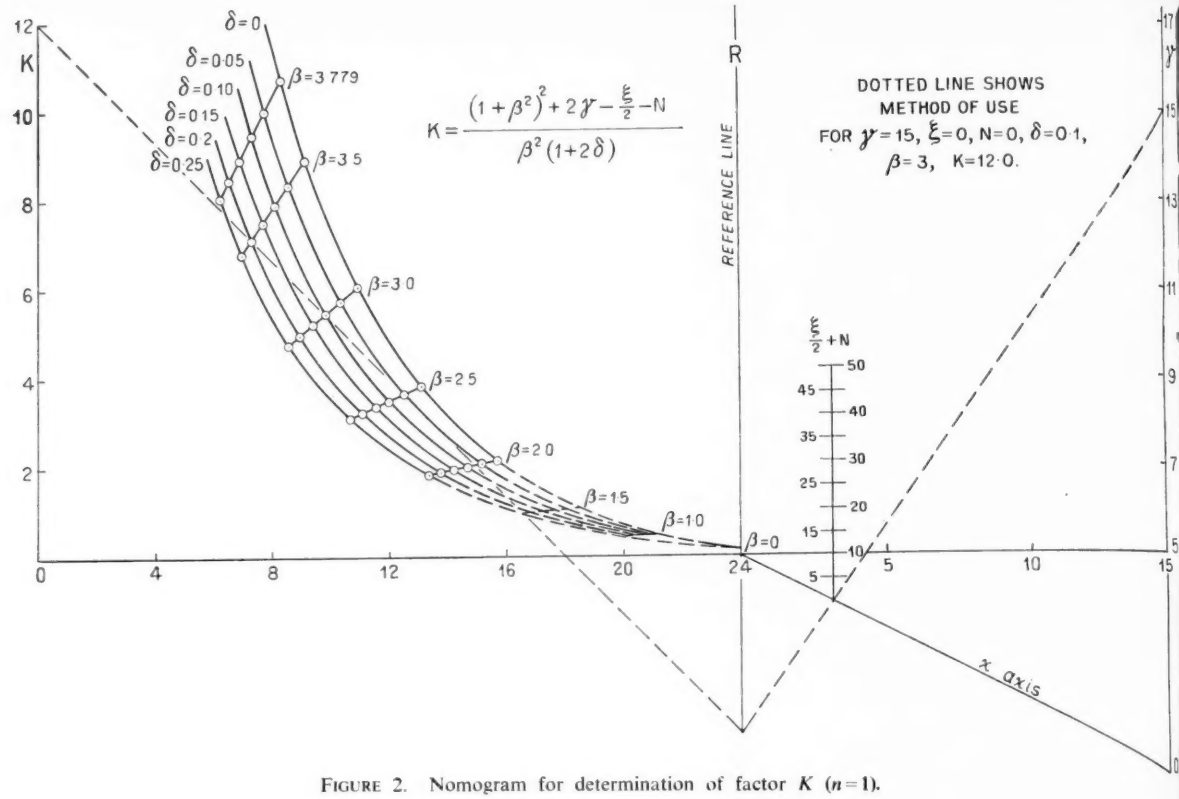

FIGURE 2. Nomogram for determination of factor K ($n=1$).

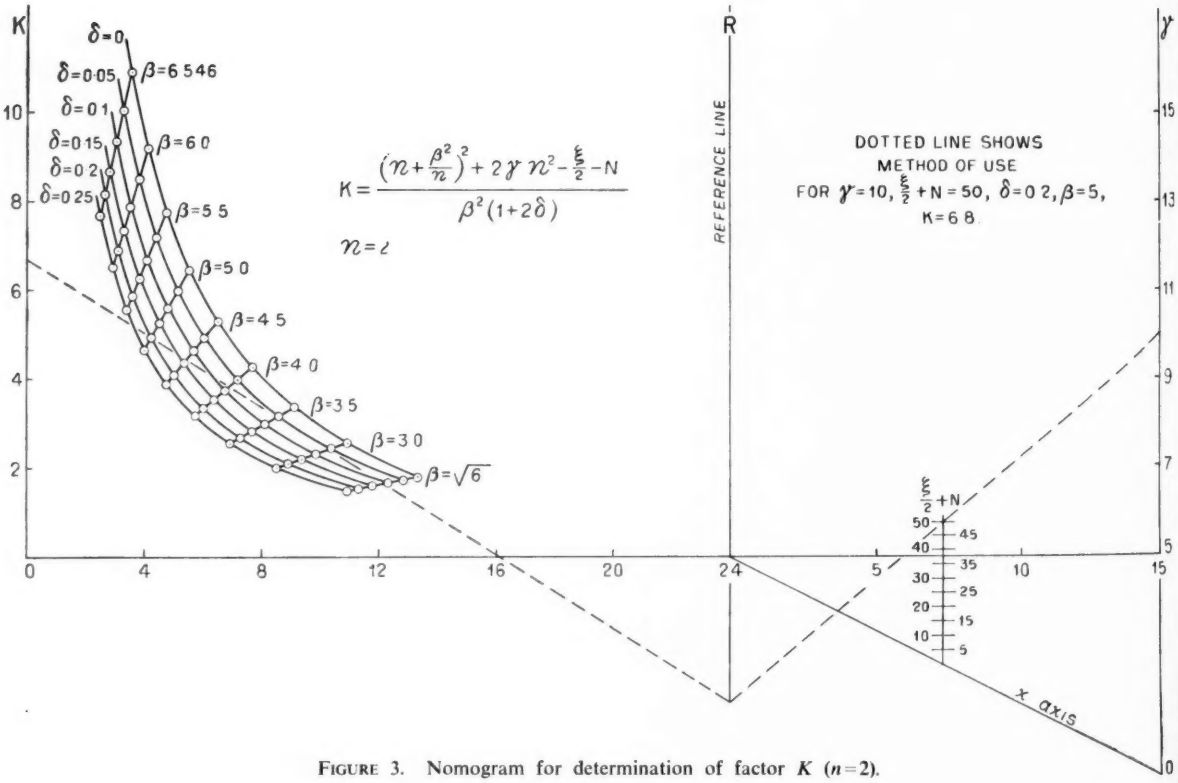

FIGURE 3. Nomogram for determination of factor K ($n=2$).

Second approximation

$$a_1 \neq 0 \qquad a_3 \neq 0$$

$$\left[a_1(1+\beta^2)^2 + 2\gamma(a_1-a_3) - \frac{\xi}{2}a_1 + N(a_1-a_3)\right] - $$

$$-K\beta^2\left[a_1 + 2\delta(a_1-a_3)\right] = 0$$

$$\left[a_3(1+9\beta^2)^2 - 2\gamma(a_1-a_3) - \frac{\xi}{2}a_3 - N(a_1-a_3)\right] -$$

$$-K\beta^2[a_3 - 2\delta(a_1-a_3)] = 0. \quad . \quad . \quad (20)$$

$$\begin{vmatrix} A - K\beta^2(1+2\delta) & X \\ X & B - K\beta^2(1+2\delta) \end{vmatrix} = 0. \quad (21)$$

Hence the value of K.

Third approximation

$$\begin{vmatrix} A - K\beta^2(1+2\delta) & X & -X \\ X & B - K\beta^2(1+2\delta) & X \\ -X & X & C - K\beta^2(1+2\delta) \end{vmatrix} = 0. \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

Fourth approximation

$$\begin{vmatrix} A - K\beta^2(1+2\delta) & X & -X & X \\ X & B - K\beta^2(1+2\delta) & X & -X \\ -X & X & C - K\beta^2(1+2\delta) & X \\ X & -X & X & D - K\beta^2(1+2\delta) \end{vmatrix} = 0. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The buckling stress predicted by the foregoing theory agrees with that found by Schildcrout and Stein[3] for the special case of an initially flat rectangular plate from the general treatment of a curved panel.

TRANSITION FROM n TO $n+1$ HALF WAVES

The value of β at which the plate changes its buckling characteristics from n half waves to $n+1$ half waves depends upon γ only, as shown later, and is independent of ξ, N and δ. As a first approximation for short plates and as an accurate value for longer plates, the "first approximation" (equation (17)) can be used for the critical value. The transition from n to $n+1$ half waves in the graph between K and β evidently occurs when the two corresponding values of K are equal.

From the first approximation, *i.e.* equation (17)

$$\left(n + \frac{\beta^2}{n}\right)^2 + 2\gamma n^2 = \left[(n+1) + \frac{\beta^2}{n+1}\right]^2 + 2\gamma(n+1)^2 \quad (24)$$

which yields on simplification

$$\beta = [n^2(n+1)^2(1+2\gamma)]^{\frac{1}{4}}. \quad . \quad . \quad (25)$$

Normally the two limits between which γ varies are 5 and 25. For these limits the value of β at which the plate starts buckling into two half waves is 2·575 and 3·779 respectively.

NOMOGRAMS

The nomogram (Fig. 2) is valid only if the plate geometry is such that it buckles into one half wave longitudinally in the direction of loading. It is not very accurate in the lower regions of β (*i.e.* $\beta < 2$) as the first approximation is used. The part of the nomogram from which accurate readings can be obtained is drawn in full lines and the dotted lines of the nomogram, if used, give only approximate values.

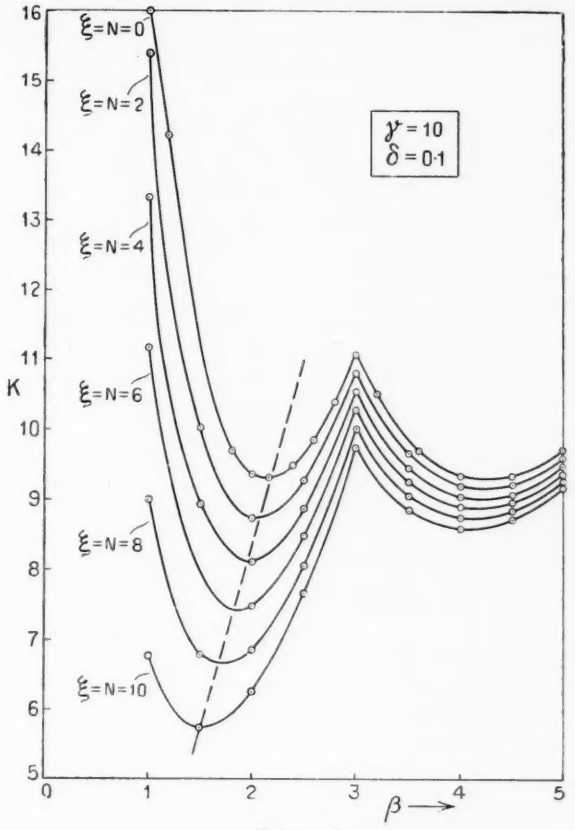

FIGURE 4.

The nomogram (Fig. 3) is valid for the plate which buckles into two half waves longitudinally and here the value of β at which the plate starts buckling into three half waves is 4·461 and 6·546 respectively.

Figure 4 is a curve between K and β using some common values of other variable parameters. Here the values of K have been calculated using even third approximation in some cases ($1 \leqslant \beta \leqslant 2$) and ($3{\cdot}028 \leqslant \beta \leqslant 4$). The dotted portion of the graph is not to be used.

ACKNOWLEDGMENT

The author is indebted to J. V. Rattayya for some valuable suggestions in the construction of the nomograms.

REFERENCES

1. FAVRE, HENRY (1948). The Influence of its Own Weight on the Stability of a Rectangular Plate. Paper presented at the Seventh International Congress for Applied Mechanics, 1948.
2. TIMOSHENKO, S. P. (1936). *Theory of Elastic Stability*, 1st Ed., p. 371. McGraw-Hill, New York, 1936.
3. SCHILDCROUT, M. and STEIN, M. (1949). Critical Axial-Compressive Stress of a Curved Rectangular Panel with a Central Longitudinal Stiffner. N.A.C.A. T.N. 1879, 1949.

Analysis of Stress Strain Curves

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IT is gratifying to learn from Mr. Nicholls (May 1955, p. 364) that he is favourably impressed with the exponential function, and it is to be hoped that he, and others interested in stress-strain relationships, may find it to be of practical value*.

While the modifications which he suggests are quite legitimate, they tend to mask the essential simplicity of the function. It would be difficult to obtain the asymptotic stress from his first equation. The second can be easily solved for strain, but the converse process is complicated by the fact that the current stress appears both inside and outside the exponential. It is surely much more straightforward, and infinitely quicker, to plot the stress-strain curve from the proof stress data and analyse it in the normal way.

In preparing his modified table, all that Mr. Nicholls has in essence done is to accept 49,700 lb./in.^{2} as the threshold stress, to reduce the characteristic strain to $24{,}000/(10{\cdot}6\times10^6)=2{\cdot}26\times10^{-3}$, and to diminish the asymptotic stress to 73,700 lb./in.^{2}, which is the value then needed to give tangential junction with the elastic line at the threshold stress. The fit is quite good, although the curve tends to run a little low at the higher stresses.

Mr. Nicholls visualises the possibility of replacing the asymptotic stress by the true stress at the maximum load. To do so indiscriminately would be exceedingly dangerous, for in most cases this critical point lies high up in the main régime of strain hardening, far above the tiny fillets in which he is interested. In general the asymptotic stress for the fillet is only just above the threshold stress for the main régime. Conceivably it could happen that the fillet occupies the whole of the available ductility, and, in such circumstances, the approximation might hold, for $S_m=S_\infty/(1+\eta_c)$, which is nearly S_∞ when η_c is very small. Alloys of low ductility and ductile materials in the heavily cold worked condition might be expected to fall into this category.

A. C. NICHOLLS

THE main reason for the inclusion of the first equation was not as a suggested modification, but rather to indicate that where proof stresses are given the simplicity of Dr. Voce's expression no longer holds. As for the second equation, the object of the rearrangement was merely to reduce the terms to one unknown and two known variables. As such it may readily be presented in a form similar to that of Figure *C*. Even so, the second equation is still dependent on a knowledge of the Limit of Proportionality and on the assumption that this knowledge is accurate.

The expression propounded by Dr. Voce undoubtedly possesses the advantages of both elegance and simplicity, provided the data are not proof stresses and permanent strains. The direct plotting of curves from such data is not really satisfactory where only three values are quoted; for instance, AP.970, Vol. 2.

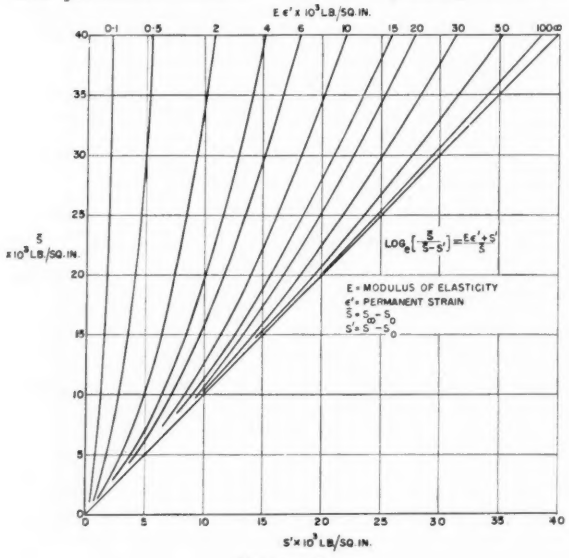

FIGURE C.

However, the following expression might yield interesting possibilities:

$$S_\infty - S = Ae^{-\varepsilon/\eta_c}$$

where ε is the fractional extension and A is a constant.

By differentiation,

$$\frac{dS}{d\varepsilon} = \frac{A}{\eta_c}e^{-\varepsilon/\eta_c}$$

which on rearrangement gives an almost identical form to Dr. Voce's basic equation. Such an expression is independent of S_0 and is simply a modified presentation of Dr. Voce's third equation.

In the example previously discussed, A would have a value of $0{\cdot}191\times10^6$ lb./in.^{2} while S_∞ and η_c would retain their earlier values of 73,700 lb./in.^{2} and $2{\cdot}26\times10^{-3}$ respectively.

But to return to the original Technical Note from which all this discussion has arisen, are the equations set forth there really all that unacceptable? The expressions of Ramberg and Osgood seem to have enjoyed a well-deserved popularity in the United States, and for many years the equations of Rao and Leggett have formed the basis of a number of curves in the Royal Aeronautical Society Data Sheets. The origin of these curves could, without much difficulty, be transferred to the *LP* were it considered desirable. Such a move, however, would not be justified while the *LP* remains such a difficult point to determine accurately.

Lastly, it is just possible that a more accurate testing technique than is at present available might reveal the *LP* to be zero and the behaviour of the material to be but a very close approximation to Hooke's Law.

See also A Practical Strain Hardening Function. E. Voce. *Metallurgia*, Vol. 51, May 1955.

THE LIBRARY
Reviews

CANADA'S FLYING HERITAGE. *Frank Ellis. University of Toronto Press, 1954. 388 pp. Illustrated. 63s.*

Frank Ellis, the author of "Canada's Flying Heritage," was born in Nottingham, England, going to Canada as a boy where his early activities in aviation resulted in his being elected a member of the Early Birds of America. A lifelong interest in flying led him to collect, and he had the foresight to preserve, letters, photographs, press clippings and other data, accumulating a formidable mass of information on which this book is based. It has been published by the University of Toronto Press, with the generous financial assistance of Imperial Oil Limited, as "a historical document of great value."

Mr. Ellis starts with an account of experiments in aircraft building in Canada from 1907 with an occasional backward glance at significant events before that date. He goes on to relate the adventures of early barnstormers up to the First World War when he concentrates on service flying and the Canadians who flew with the Royal Flying Corps. He describes the activities of ex-wartime flyers who, wanting to stay in aviation, had little opportunity apart from daredevil exhibition flying. The formation of the Canadian Air Force (later to become the Royal Canadian Air Force) and flying clubs throughout the country, provided further opportunities, giving considerable impetus to the development of aviation which was to receive such enormous stimulation in the Second World War.

It is interesting to be reminded that a Canadian, the late Wallace R. Turnbull, who became a Fellow of the Royal Aeronautical Society, was responsible for Canada being recognised as the birthplace of the controllable pitch propeller.

Trans-Continental and trans-Atlantic flying—nearly all the latter started or finished in the Maritime Provinces or Newfoundland (now the tenth province of Canada)—are dealt with at some length, but perhaps the most absorbing section of this history is that which describes the spectacular early flights into the Arctic by bush pilots with their determined endurance of incredible hardships, the searches for those lost in that frozen hinterland, and the scientific achievements resulting.

Certain aspects of flying in Canada have been omitted — for instance, the development of the airway system across the continent which involved several years of hard and dangerous work in searching for suitable sites which evolved into the present chain of airports. There is only a brief reference to the airlines which have reduced travel across the country to hours instead of days, and north to the Arctic to hours from weeks and possibly months. The air mail story is, however, covered in some detail.

The book has many photographs and several appendices, two of which list the names of the winners of the well-known McKee and Webster Trophies. The size and weight of the book make it rather unwieldy.

—J. H. TUDHOPE.

HUMAN ENGINEERING GUIDE FOR EQUIPMENT DESIGNERS. *Wesley E. Woodson. University of California Press/Cambridge University Press, 1954. 246 pp. Illustrated. 26s.*

Those who are familiar with the wide scope of the term "human engineering data" will need no second bidding to place this book on their ready-reference shelf. It is the first modern ABC of the subject to become commercially available in a handy attractive *format*—and moreover, the price is reasonable. Naturally this publication cannot match the comprehensive sweep of its limited edition big brother —the Tufts College *Handbook of Human Engineering Data*, nor is it specifically aeronautical like Dr. Ross McFarland's well-known books. But it does succeed in doing exactly what it sets out to do—to provide a *guide* for the designer of *any* equipment meant for use by human beings. The profuse and apt illustrations are matched by a readable text and good book design.

Most important of all, this book is the ideal introduction for any designer who is suspicious of the subject and may be wondering what the fuss is all about. In its essentials, human engineering is a subject as old as civilisation—namely "the design of tools and tasks for average humans involving minimum effort and maximum sustained accuracy in operation." Only in the last few decades have equipment designers been forced to seek the advice of physiologists and psychologists and to ask whether human beings can do the impending tasks of an advancing technology. (*See*, for example, the Proceedings of the Ergonomics Research Society). The common meeting ground for the mechanical and the human scientists has been called "human engineering," and the results are useful for designing anything from a pencil to a supersonic cockpit.

For British readers, the introductory pages may prove a little indigestible, but there can be no difficulty in following the five main sections labelled:

1. Design of equipment and workspace.
2. Vision.
3. Audition (hearing).
4. Other factors (including, for example, principles of motion economy; the accuracy of reaching movements and sensitivity to various stimuli).

Each section is supported by a list of References and the whole book is completed by an extremely useful classified Bibliography, together with a suggested reference library. It is probably inevitable that in an American book, the references to British work cannot be so comprehensive or topical as those for American work. The English publishers would perform an invaluable service if they could produce an Addendum listing publications available in England and Europe under the same classified headings.

The book does not claim to be comprehensive, but it seems strange that no attempt has been made to summarise the learning processes in simple or complex tasks.—H. C.

THE JET AIRCRAFT OF THE WORLD. *William Green and Roy Cross. Macdonald, London, 1955. 176 pp. Illustrated. 30s.*

This beautifully made reference book deals not only with the most recent jet aeroplanes, but is a complete history of jet development. The main section describes jet aeroplanes from the Heinkel 176 (of June 1939) to the McDonnell F 101A (October 1954) chronologically in the order of their first flights. For each aeroplane at least a three view drawing, several photographs and a detailed description are given. Several of the more important

aeroplanes are given extended treatment with the drawings in tone and photographs showing every variant. The book contains no less than twenty photographs of the Meteor in various guises. It is claimed, in fact, that "every jet built and flown" is illustrated.

The choice of chronological order, irrespective of type or nationality of the aeroplane, offers the reader an opportunity of judging progress in the various countries. The story begins with the twenty different designs from five countries which flew before the end of the war and continues with the 150 designs which have flown in the ten prolific years since. Not forgotten is the story of the engines which power the aeroplanes. A history of engine development in various countries, a table of jet engine characteristics and a section devoted to jet helicopters complete a first-class reference history book. The quality of the paper and printing is also excellent.—A. H. YATES.

THE HELICOPTER AND HOW IT FLIES. *John S. Fay. Pitman, 1954. 105 pp. 10s. 6d.*

Reviewed in November 1954 Journal, page 789.

In Captain Liptrot's review of Mr. Fay's book *The Helicopter and How it Flies* the third paragraph of the review reads:—

> "In Chapter II, dealing with the helicopter in vertical powered flight, the opening paragraphs state that to make any object leave the ground an upward force greater than the weight must be applied, and in the accompanying sketch of a helicopter the lift vector is shown larger than the weight vector. In all steady conditions of flight, of course, the rotor thrust is substantially equal to the weight, and a helicopter climbs not because the rotor thrust is greater than the weight but because the power available at the rotor is greater than that required to develop the thrust and overcome drag, so that work can be done against gravity to raise the aircraft."

This statement is unfair to Mr. Fay. In steady vertical ascent the lift is greater than the weight (though it may be only a little greater); it may not be incorrect to say that the lift or thrust is "substantially equal" to the weight but it may be seriously misleading to do so. In fact two conditions must be satisfied for steady vertical ascent:—

(1) Lift or thrust = Weight + Drag > Weight.

(2) Sufficient power must be available.

Your reviewer seems to think that only the second of these is significant.

H. B. SQUIRE.

I am afraid that Professor Squire is divorcing the paragraph in question from its context, and is misunderstanding my real criticism. In the preceding paragraph I pointed out that in his preface the author says that he has tried to avoid the pitfalls which one so often finds in books which attempt to simplify a complex subject, but that in one or two instances he had not wholly succeeded. The paragraph to which exception is taken was drawing attention to one of these.

In this paragraph I was not criticising the statement that rotor thrust is greater than weight in the same sense that Professor Squire quotes it, but simply pointing out that the presentation of vertical climb might be misleading to the uninitiated, for whom the book was intended, to the extent that it gives the impression that a helicopter climbs vertically because the rotor thrust is greater than the weight, in other words that it is physically hauled up by an upward force greater than the downward force, no mention being made of the fact that work has to be done. Surely this was fair comment?

I would submit that the second sentence of the offending paragraph states the same two conditions as those given by Professor Squire, except that I wrote "rotor thrust is substantially equal to the weight" instead of "thrust equals weight plus drag." I do not consider that I was "seriously misleading" not to have given a quantitative indication of what I meant by "substantially equal." If we are to be pedantic I would point out that this equality of thrust and, shall we call it, "effective weight" is the condition which must be satisfied for sustentation, without which flight and therefore climb is impossible. It is certainly a pre-requisite for climb, but climb as such is a function only of excess horsepower available at the rotor.

CAPTAIN R. N. LIPTROT.

Additions to the Library

A.S.T.M. SYMPOSIUM ON EFFECT OF CYCLIC HEATING AND STRESSING ON METALS AT ELEVATED TEMPERATURES. S.T.P. 165. A.S.T.M. 1954.

A.S.T.M. 1953 REFERENCES ON FATIGUE. S.T.P. 9-E. A.S.T.M. 1954.

Baker, C. TECHNICAL PUBLICATIONS. Chapman & Hall. 1955.

Booth, A. D. NUMERICAL METHODS. Butterworth. 1955.

Brooks, B. T. and A. E. Dunstan (*General Editors*). THE SCIENCE OF PETROLEUM. VOL. V. PART III. REFINERY PRODUCTS. O.U.P. 1955.

Jaworski, A. THE EFFECT OF STANDARD CHARGES ON CANADIAN AIRPORT OPERATIONS. (Reprint) Jnl. Air Law and Commerce. 1954.

Knudsen, J. G. and D. L. Katz. FLUID DYNAMICS AND HEAT TRANSFER. University of Michigan. 1954.

Ludovico, *General* D. DE SEVERSKY AND DOUHET: A CRITICAL COMPARISON. (Offprint). Rivista Aeronautica. 1954.

Ministerium für Wirtschaft und Verkehr. BEITRÄGE ZUM INTERNATIONALEN LUFTRECHT. Droste-Verlag. Düsseldorf. 1954.

National Bureau of Standards. TABLE OF SALVO KILL PROBABILITIES FOR SQUARE TARGETS. (App. Maths. Series 44). U.S.G.P.O. 1954.

Ower, E. THE MEASUREMENT OF AIR FLOW. 3rd edition. Chapman & Hall. 1949.

Perkins, C. D. (*General Editor*). FLIGHT TEST MANUAL. VOL. 1. PERFORMANCE. AGARD. 1955.

Spalding, D. B. SOME FUNDAMENTALS OF COMBUSTION. Butterworth. 1955.

Taylor, J. W. R. CONTINENTAL MILITARY AIRCRAFT. Ian Allan Ltd. 1955.

Taylor, J. W. R. BRITISH MILITARY AIRCRAFT. Ian Allan Ltd. 1955.

Thacker, *Professor* M. S. THE HIGH TENSION SPARK PLUG. (Mem. Ind. Inst. Sc. No. 2.) Indian Inst. Science. 1955.

Truscott, W. T. AIRCRAFT CONTROL—A SURVEY. A.E.S.D. 1955.

Reports

AERODYNAMICS

Boundary Layer

Free-flight measurements of turbulent-boundary-layer skin friction in the presence of severe aerodynamic heating at Mach numbers from 2·8 to 7·0. S. C. Sommer and B. J. Short. N.A.C.A., T.N. 3391 (March 1955).

Measurements of average skin friction of the turbulent boundary layer have been made in free flight at high rates of heat transfer at high Mach numbers. The results are appreciably higher than zero-heat-transfer wind-tunnel data. The T' method for laminar boundary layers, slightly modified, is shown to agree with results of this and other investigations at widely different Mach numbers and heat-transfer conditions.—(1.1.3.4).

Laminar boundary layer behind shock advancing into stationary fluid. H. Mirels. N.A.C.A., T.N. 3401 (March 1955).

The laminar compressible boundary layer induced by a shock wave advancing into a stationary fluid bounded by a wall was studied. For weak shock waves, the boundary layer is identical with that which occurs when an infinite wall is impulsively set into uniform motion (Rayleigh problem). A numerical solution was required for strong shocks. Velocity and temperature profiles, recovery factors, and skin-friction and heat-transfer coefficients are tabulated for a wide range of shock strengths.—(1.1.1.3).

Compressible Flow

See also Wings and Aerofoils and Testing and Instruments

An investigation of drains discharging liquid into subsonic and transonic streams. A. R. Vick and F. V. Silhan. N.A.C.A., T.N. 3359 (March 1955).

Results of an investigation on the characteristics of drains discharging liquid into an air stream at Mach numbers from 0·5 to 1·3 are presented in the form of surface stain patterns, schlieren photographs of the flow, and drag measurements for drains of circular, elliptical, and aerofoil cross-sectional shapes. Variables whose influence have been investigated include Mach number, liquid reservoir pressure, drain extension, angle of sweep, and end shape. Vent pressure data are presented as differentials between the free-stream and drain static pressure for various tube configurations.—(1.2.2 × 1.5.1).

An accurate and rapid method for the design of supersonic nozzles. I. E. Beckwith and J. A. Moore. N.A.C.A., T.N. 3322 (February 1955).

A procedure is given for designing two-dimensional nozzles in which the streamline co-ordinates are computed directly from tabulated flow parameters and appropriate equations. The method of characteristics was used to obtain the first part of the flow which consists of a continuous expansion from a uniform sonic flow to a radial flow. The Foelsch equations are used for the transition from this radial flow to the final uniform flow.—(1.2.3 × 1.12.1.3).

Theoretical calculations of the pressures, forces and moments due to various lateral motions acting on thin isolated vertical tails with supersonic leading and trailing edges. M. Margolis. N.A.C.A., T.N. 3373 (March 1955).

Expressions based on linearised thin aerofoil theory for supersonic speeds are derived for the velocity potentials and pressure distributions due to various lateral motions for a family of thin isolated vertical tails with arbitrary sweepback and taper ratio. Motions treated are steady rolling, steady yawing, constant sideslip, and constant lateral accelerations.—(1.2.3).

Axially symmetric shapes with minimum wave drag. M. A. Heaslet and F. B. Fuller. N.A.C.A., T.N. 3389 (February 1955).

Optimum bodies consisting of a basic cylinder with added peripheral volume are derived and presented in terms of the effective radius-length ratio. Variation of this parameter from 0 to ∞ encompasses the spectrum of results from slender to two-dimensional. A reciprocal theorem leads to simple interpretations of variational problems.—(1.2.3).

An experimental investigation of the base pressure characteristics of nonlifting bodies of revolution at Mach numbers from 2·73 to 4·98. J. O. Reller and F. M. Hamaker. N.A.C.A., T.N. 3393 (March 1955).

Base pressure characteristics of related non-lifting bodies of revolution were investigated at free stream Mach numbers from 2·73 to 4·98 and Reynolds numbers from $0{\cdot}6 \times 10^6$ to $8{\cdot}8 \times 10^6$. The basic body shape was a 10-calibre tangent ogive with a cylindrical afterbody. The variation of base pressure coefficient with free stream Mach number and Reynolds number was determined for laminar, transitional and turbulent boundary layer flow. Some effects of body fineness ratio, nose-profile shape, and afterbody shape (boat-tail) were also investigated.—(1.2.3).

Control Surfaces

A rapid approximate method for the design of hub shroud profiles of centrifugal impellers of given blade shape. K. J. Smith and J. T. Hamrick. N.A.C.A., T.N. 3399 (March 1955).

A rapid approximate method for the design of centrifugal compressors of given blade shape with compressible non-viscous flow characteristics has been developed using techniques based upon stream-filament theory. Axial symmetry is assumed, but meridional plane forces derived from tangential pressure gradients are included. The method was applied to the design of an impeller to determine the approximate maximum meridional streamline spacing that could be used.—(1.3.2.2).

Fluid Dynamics

See also Testing and Instruments

Some measurements of time and space correlation in a wind tunnel. A. Favre et al. N.A.C.A., T.M. 1370 (February 1955).

Results are presented of research obtained by an apparatus for measurement of time and space correlation and by a spectral analyser in the study of the longitudinal component of turbulence velocities in a wind tunnel downstream of a grid of meshes. Application to the case of a flat plate boundary layer is illustrated.—(1.4.2).

Internal Flow

See also Compressible Flow

Preliminary china clay tests on rotary cascade blade surfaces. P. V. Crooks and W. Howard. A.R.L./ME. 196 (December 1954).—(1.5.2.1).

A note on secondary flow in rotating radial channels. J. J. Kramer and J. D. Stanitz. N.A.C.A. Report 1179 (1954).

A general vector differential equation for the vorticity component parallel to a stream line is derived for steady, non-viscous and incompressible flow in a rotating system. By restricting it to rotating radial channels and further simplifying assumptions this equation is then simplified and used to solve for the secondary vorticity, the vorticity component parallel to the stream line, in three special cases involving different stream tube geometries.—(1.5.2.2).

An evaluation of non-Newtonian flow in pipe lines. R. N. Weltmann. N.A.C.A., T.N. 3397 (February 1955).

An analysis is presented of a method for determining pressure losses due to the flow of non-Newtonian materials in pipe lines by using basic flow data obtained from measurements of flow curves, which are rate-of-shear-shearing-stress curves. The advantages of properly designed rotational viscometers over capillary viscometers for measuring these flow curves and interpreting them to obtain the basic flow parameters are discussed.—(1.5.1.1).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

Analysis of errors introduced by several methods of weighting nonuniform duct flows. DeMarquis D. Wyatt. N.A.C.A., T.N. 3400 (*March* 1955).

Three typical duct flow profiles have been numerically analysed to determine the errors introduced by commonly used averaging methods in the resultant uniform flow properties. The analysis covers a range of subsonic duct Mach numbers, but is confined to flows having uniform static pressure and total temperature. An averaging method yields uniform properties that satisfy the integrated mass and momentum of the non-uniform flow.—(1.5.1).

PERFORMANCE ESTIMATION

Steady properly-banked turns of turbojet-propelled airplanes. A. Miele. N.A.C.A., T.M. 1382 (*March* 1955).

The problem of a jet-propelled aeroplane in a steady turn is analysed for the case of parabolic and non-parabolic aircraft polars. A general solution is obtained and the special cases of maximum banked turn, maximum angular velocity turn and minimum radius turn are investigated. The jet and reciprocating propelled aeroplane is compared briefly. Compressibility effects are considered.—(1.7).

STABILITY AND CONTROL

See also AEROELASTICITY

Preliminary investigation of a stick shaker as a lift-margin indicator. J. P. Trant. N.A.C.A., T.N. 3355 (*February* 1955).

Preliminary tests with simulator equipment were made to determine the ability of subjects to use frequency or amplitude of vibration of the pilot's control stick, or both, as an indicator for maintaining a desired lift margin below the stall.—(1.8.2 × 4.2.3).

Static stability of fuselages having a relatively flat cross section. W. R. Bates. N.A.C.A., T.N. 3429 (*March* 1955).

Results are given of force tests and flow surveys made in the Langley free-flight tunnel to determine the static stability characteristics of several fuselages having a relatively flat cross section and a high fineness ratio.—(1·8).

THERMO-AERODYNAMICS

Turbulent-heat-transfer measurements at a Mach number of 2·06. *M. J. Brevoort and B. Rashis. N.A.C.A., T.N.* 3374 (*March* 1955).

An axially symmetric annular nozzle was used to obtain essentially flat plate data on turbulent heat transfer coefficients and temperature recovery factors. These test results are for Mach number 2·06 and for a Reynolds number range of $1{\cdot}7 \times 10^6$ to $8{\cdot}8 \times 10^7$.—(1.9.1).

One-dimensional calculation of flow in a rotating passage with ejection through a porous wall. E. R. G. Eckert et al. N.A.C.A., T.N. 3408 (*March* 1955).

A method is developed for the determination of the local wall permeability necessary to obtain a prescribed local distribution of ejected gas or for the determination of the local distribution of ejected gas resulting from a given local wall permeability. Sample calculations are presented for two blind radial passages of a rotating transpiration cooled turbine blade. The effects of passage area variation, passage inlet pressure, and passage inlet Mach number are investigated.—(1.9.1).

WINGS AND AEROFOILS

Aerodynamic forces on rectangular wings oscillating in a supersonic air stream. W. E. A. Acum. R. & M. 2763 (*August* 1950, *published* 1954).

The aerodynamic forces on rectangular wings of various aspect ratios describing simple harmonic oscillations of small amplitude in a supersonic air stream are determined. Linearised theory is used and numerical solutions are derived by the method of "Relaxation."—(1.10.1.2 × 2.0).

*The turbulent boundary layer on the articulated nose of a thin wing provided with air jets. R. A. Wallis. A.R.L./A.*141 (*October* 1954).

The boundary layer flow on the nose of a thin wing has been investigated experimentally. Known methods of computing the growth of turbulent boundary layers in adverse pressure gradients have been used and compared with the experimental data. A simple method of computing boundary layer properties and predicting the likelihood of separation has been suggested.—(1.10.2.1).

Theoretical study of the transonic lift of a double-wedge profile with detached bow wave. W. G. Vincenti and C. B. Wagoner. N.A.C.A. Report 1180 (1954).

Numerical calculations are described of the aerodynamic characteristics at small angle of attack of a thin, doubly symmetrical, double wedge profile in the range of supersonic flight speed in which the bow wave is detached. The analysis is carried out within the framework of the transonic (non-linear) small-disturbance theory.—(1.10.1.1 × 1.2.2).

Lift on a bent, flat plate. F. Keune. N.A.C.A., T.M. 1340 (*February* 1955).

The lift on a bent, flat plate is calculated exactly by the use of conformal mapping. Results are presented in terms permitting direct determination of the angle of zero lift, the lift coefficient, and the lift-curve slope for any flap-chord ratio, flap-deflection angle, and angle of attack.—(1.10.1.1 × 1.3).

Flight measurements of the velocity distribution and persistence of the trailing vortices of an airplane. C. C. Kraft. N.A.C.A., T.N. 3377 (*March* 1955).

Measurements have been made in flight of the velocity distribution and persistence of the trailing vortices of a propeller-driven fighter-type aeroplane. The vortices were marked in the atmosphere with smoke and were penetrated by a jet aeroplane equipped with a high frequency angle of attack vane and a sensitive total-pressure instrument. Photographs of the trailing-vortex filaments were also made. —(1.10.2.2 × 5.3).

Second-order subsonic airfoil-section theory and its practical application. M. D. Van Dyke. N.A.C.A., T.N. 3390 (*March* 1955).

Several recent advances in subsonic compressible flow theory are combined into a unified second order theory for two-dimensional aerofoils. Solutions are given for a number of profiles, and are compared with the results of other theories and of experiment. A straightforward computing scheme is outlined for calculating the pressures on any aerofoil at any angle of attack.—(1.10.1.1).

TESTING AND INSTRUMENTS

See also COMPRESSIBLE FLOW

*Tuyères supersoniques a col réglable. M. Menard et al. Publications Scientifiques et Techniques du Ministère de L'Air. No. N.T.*51 (1955).—(1.12.1.3).

A dye-tracer technique for experimentally obtaining impingement characteristics of arbitrary bodies and a method for determining droplet size distribution. U. H. von Glahn et al. N.A.C.A., T.N. 3338 (*March* 1955).

A dye-tracer technique has been developed from which the droplet impingement characteristics of bodies can be determined by colorimetric analysis. The technique is applicable to various wind tunnels provided that the humidity of the air stream can be maintained near saturation. It is also shown how the droplet size distribution of the impinging cloud may be determined by relating the experimental impingement characteristics of a body to the theoretical trajectory results for the same body.—(1.12.1 × 1.4.1).

Generalization of gas-flow-interferometry theory and interferogram evaluation equations for one-dimensional density fields. W. L. Howes and D. R. Buchele. N.A.C.A., T.N. 3340 (*February* 1955).

Generalised equations concerned with gas flow interferometry are applied in developing interferogram evaluation equations for one-dimensional density fields. Theoretical limitations and systematic errors of the equations are investigated. Criteria for applicability and for avoiding apparent-ray-trace crossing are presented with analytical and experimental checks of the validity of the evaluation equations. Theoretical results are compared with those of previous analyses. —(1.12.0).

A theory for predicting the flow of real gases in shock tubes with experimental verification. R. L. Trimpi and N. B. Cohen. N.A.C.A., T.N. 3375 (*March* 1955).

The non-linear characteristic differential equations applicable to a quasi one-dimensional unsteady channel flow with friction and heat transfer are linearised and integrated in functional form for the particular study of small perturbations from ideal shock-tube flows.—(1.12.1.3 × 1.2.3.1).

Flight testing by radio remote control-flight evaluation of a beep-control system. H. L. Turner et al. N.A.C.A., T.N. 3496 (*March* 1955).

A comparison between manual control and remote control showed that a beep-type, remote control system was, in general, a satisfactory means of control for conducting standard handling quality flight tests. The dynamic characteristics of the aeroplane-autopilot combination and the selection of the proper parameter adjustments are discussed. —(1.12.2).

AEROELASTICITY

See also AERODYNAMICS: WINGS AND AEROFOILS

A simplified method for calculating aeroelastic effects on the roll of aircraft. J. M. Hedgepeth et al. N.A.C.A., T.N. 3370 (*March* 1955).

An approximate linearised lifting surface theory is used in conjunction with structural influence coefficients to formulate a method for analysing the aeroelastic behaviour in roll of an aircraft. Rolling effectiveness and aileron reversal speed are computed by the use of a Galerkin type procedure. Results obtained for two example configurations by using this method are compared with the results obtained by using the more refined method of N.A.C.A. T.N. 3067.—(2.0 × 1.8.1.2).

AIRCRAFT OPERATION

See also AERODYNAMICS: WINGS AND AEROFOILS

Protection of aircraft fuel tanks against explosion hazards using inert combustion products. E. M. Goodger et al. CoA Report No. 85 (*October* 1954).

Combustion products have been suggested as an alternative and continuously available supply of inert gases. This report describes experiments made on sampling from the primary zone of a Derwent I chamber, and on the testing of various automatic control devices suitable for an inert gas generator. —(5.3).

FUELS AND LUBRICANTS

See also THERMODYNAMICS

A thermal equation for flame quenching. A. E. Potter and A. L. Berlad. N.A.C.A., T.N. 3398 (*February* 1955).

A thermal quenching equation is derived; the equation is essentially an extension of a previously proposed diffusional concept. The equation was tested, using published quenching distance data for propane oxygen-nitrogen flames, which include the effect of oxygen-nitrogen ratio, equivalence ratio, pressure, and initial temperature.—(14.0).

Chain breaking and branching in the active-particle diffusion concept of quenching. F. E. Belles and A. L. Berlad. N.A.C.A., T.N. 3409 (*February* 1955).

General quenching distance equations that take into account gas-phase chain breaking and branching and the effect of the wall efficiency for destruction of active particles are derived as extensions of the original simple theory of quenching by diffusion of active particles. The general characteristics of the equations are discussed.—(14·0).

MATERIALS

*The electropolishing of chromium and chromium base alloys. K. F. Lorking and S. T. Quaass. A.R.L./MET.*3 (*October* 1954).

A process for electropolishing chromium and chromium-based alloys has been developed. The polishing bath contains orthophosphoric acid, sulphuric acid and water or orthophosphoric acid alone. Conditions are given for obtaining rapid smoothing, polishing and a finish suitable for metallographic examination. The probable mechanism of polishing and the anodic processes are described.—(21.5).

*On the age hardening of alloys based on aluminium-zinc magnesium system. I. J. Polmear. A.R.L./MET.*9 (*October* 1954).

The available literature concerning the effect of age hardening on the changes in structure and properties in alloys of the 75S type has been critically surveyed. Due to the complexity of the process preliminary consideration has been given to precipitation phenomena in the simpler aluminium base alloys upon which the 75S series are based. —(21.1).

A thermodynamic approach to the chromium-tungsten phase diagram in the temperature range 800°*C to* 1,500°*C. I. J. Polmear. A.R.L./MET.*11 (*November* 1954).

The chromium-tungsten phase diagram has a miscibility gap below 1,500°C. and the solubility data have been shown to conform, approximately, with the sub-regular solution model proposed by Bardy. The existence of pre-precipitation processes is discussed from both the theoretical and practical aspects. Brief reference is made to the possible behaviour of the alloys during heat treatment and upon service at high temperatures.—(21.1).

Méthode d'analyse chimique des alliages réfractaires. V. Duriez and J. Barboni. O.N.E.R.A. Note Technique No. 24 (1955).—(21.1).

New methods for computing parameters of complete or truncated distributions. W. Weibull. FFA Report 58 (*February* 1955).

Two new types of distribution moments are introduced which may be used with advantage for computing the parameters of a large family of functions. The procedure is demonstrated on a particular distribution function which has been found by experience to fit various static and fatigue strength data with fidelity.—(21.2.0 × 22.1).

Intergraular corrosion of high-purity aluminum in hydrochloric acid. 1—Effects of heat treatment, iron content, and acid composition. M. Metzger and J. Intrater. N.A.C.A., T.N. 3281 (*February* 1955).

The inter-granular corrosion of high purity aluminium in hydrochloric acid was studied as a function of iron content, heat treatment, and acid composition under conditions where the rate of inter-granular penetration was of the order of one millimetre per week.—(21.2.2).

Study of effects of microstructure and anisotropy on fatigue of 24*S-T4 aluminum alloy. H. A. Lipsitt et al. N.A.C.A., T.N.* 3380 (*March* 1955).

The results are given of an investigation of the statistics of the effects of variation in microstructure (extruded and extruded plus recrystallised) on the fatigue properties of 24S-T4 aluminium alloy notched specimens tested in both the longitudinal and transverse directions.—(21.2.2).

MATHEMATICS

See also MATERIALS

*Méthodes de différentiation et d'intégration numériques (applications). A. Ziller. Publications Scientifiques et Techniques du Ministère de L'Air. No. N.T.*50 (1955).—(22.1).

Ill-conditioned matrices. B. Langefors. SAAB TN 22 (*June* 1953).

The errors occurring in the solutions of systems of equations as a consequence of limited accuracy in the coefficients are discussed. Applications to inversion of ill-conditioned matrices, to numerical computations and to analog computors are given.—(22.1).

MECHANICAL ENGINEERING

Analytical derivation and experimental evaluation of short-bearing approximation for full journal bearings. G. B. DuBois and F. W. Ocvirk. N.A.C.A. Report 1157 (1953).

An approximate analytical solution including the effect of end leakage from the oil film of short plain bearings is presented because of the importance of endwise flow in

sleeve bearings of the short lengths commonly used. Methods are also discussed for approximating a maximum bearing temperature for pressure-lubricated bearings and for evaluating the effect of deflection in misalignment on the eccentricity ratio at the ends of a bearing. (Formerly T.N. 2808).—(23.2.1).

Experimental investigation of misalining couples and eccentricity at ends of misalined plain bearings. G. B. DuBois et al. N.A.C.A., T.N. 3352 (*February* 1955).

The behaviour of full journal bearings under steady load when acted on by a steady misaligning couple was investigated experimentally. Displacements of the ends of the journal axis were measured with either an axial couple applied in the plane of the central load or a twisting couple in the plane normal to the central load. Oil flow rate and bearing temperature measurements were also made to determine the effect of misaligning couples on these quantities.—(23.2.1).

POWER PLANTS

Assessment of a proposed jet engine icing test bed for simulating high speed flight. D. A. J. Millar. N.A.E. LR-124 (*February* 1955).

The possibilities of a tunnel were determined by calculation and model tests for icing tests of jet engines, in which the conditions of high speed flight could be produced. A workable configuration is proposed, employing the engine jet as an ejector to help drive the tunnel. Flight speeds from 230 to 500 m.p.h. could be simulated with the single configuration.—(27.1).

Analytical determination of effect of water injection on power output of turbine-propeller engine. A. O. Ross and M. C. Huppert. N.A.C.A., T.N. 3403 (*March* 1955).

An analysis is presented to show the effect of evaporative cooling of the charge air during compression on the performance of a turbine-propeller engine incorporating a centrifugal compressor. Calculations were made with water as the cooling agent for compressor tip speeds of 1,200, 1,500 and 1,800 feet per second.—(27.1).

PRODUCTION ENGINEERING

The application of Memo-Motion to industrial operation. C. J. Norbury. CoA Report No. 86 (*December* 1954).

The field of application of Memo-Motion Study was investigated, and its use extended into new fields by developing apparatus that could take photographs at intervals varying from two per second to one every four hours.—(28).

STRUCTURES

Loads

Estimates of probability distribution of root-mean-square gust velocity of atmospheric turbulence from operational gust-load data by random-process theory. H. Press et al. N.A.C.A., T.N. 3362 (*March* 1955).

Relations are derived between the peak gust loads experienced in aeroplane operations and the probability distribution of root-mean-square gust velocity. These relations are applied in the analysis of operational data on peak gust accelerations to derive estimates of the probability distribution of root-mean-square gust velocity. The application of these results to gust load calculations for other aeroplane operations is also considered briefly.—(33.1.1.).

An analysis of accelerations, airspeeds, and gust velocities from three commercial operations of one type of medium-altitude transport airplane. T. L. Coleman et al. N.A.C.A., T.N. 3365 (*March* 1955).

Time-history data obtained by the N.A.C.A. VGH recorder from one model of a four-engined civil transport aeroplane during operations on three routes are analysed to determine the magnitude and frequency of occurrence of gust velocities, gust and manoeuvre accelerations, and the associated air speeds. Variations of the gusts and gust accelerations with route and flight condition are indicated. Estimates of the overall gust and gust-load histories for extended operations on one route are obtained by supplementing the data from the N.A.C.A. VHG recorder with available data from the N.A.C.A. V-G recorder.—(33.1.1 × 33.1.2).

Analysis of accelerations, gust velocities, and airspeeds from operations of a twin-engine transport airplane on a trans-continental route from 1950 *to* 1952. *T. L. Coleman and W. G. Walker. N.A.C.A., T.N.* 3371 (*February* 1955).

VGH time-history data obtained from one type of twin-engined transport aeroplane during operations from 1950 to 1952 on a trans-continental route are analysed in order to determine the magnitude and frequency of occurrence of gust accelerations, gust velocities, and the associated air speeds and altitudes.—(33.1.1 × 33.1.2).

Theory and Analysis

Solution of a load diffusion problem by relaxation methods. G. Vaisey and W. S. Hemp. CoA Note No. 17 (*November* 1954).

The need to generalise the usual assumptions made in the analysis of load diffusion problems has been emphasised by recent experimental work which has shown the importance of bending of the edge members. Direct mathematical solution of the plate problems which arise is hardly feasible and so a numerical solution using the "relaxation method" is carried out.—(33.2.1).

*A comparison of the elastic and plastic solutions of the uniform torsion problem of a circular ring. W. Freiberger and G. Watterson. A.R.L./SM.*226 (*October* 1954).

The methods proposed in Reports SM.122 and SM.213 for the analysis of a circular ring under torsion arising from given axial forces in the elastic and perfectly plastic conditions respectively, are compared.—(33.2.4.10.5).

The effect of sheet thickness and overlap on the fatigue strength at repeated tension of Redux bonded 75 *S-T clad simple lap joints. F. A. Jacobs and A. Hartman. N.L.L. Report M.*1969 (*October* 1954).

Fatigue tests were carried out on Redux bonded 75 S-T clad simple lap joints to obtain data on the relation between sheet thickness and overlap, and the fatigue strength.—(33.2.4.13.10).

A suggested method for calculating the stresses in wings with non-rectangular plates. B. Langefors. SAAB, T.N. 23 (*May* 1953).

A method is suggested for the analysis of oblique plates by the aid of superposition of elementary solutions. A simple method for using the results of the analysis of oblique plates in connection with structural analysis of swept wings is shown.—(33.2.4.7.0).

Exact reduction and solution by parts of equations for elastic structures. B. Langefors. SAAB, T.N. 24 (*October* 1953).

Matrix equations for elastic structures (and similar physical systems) are established by using only elastic and topological properties. (Previous procedures have used elastic, topological and one or more energy or work properties).—(33.2.1).

Analysis of behavior of simply supported flat plates compressed beyond the buckling load into the plastic range. J. Mayers and B. Budiansky. N.A.C.A., T.N. 3368 (*February* 1955).

The post-buckling behaviour of a simply-supported square flat plate with straight edges compressed beyond the buckling load into the plastic range is analysed. The method of analysis involves the application of a variational principle of the deformation theory of plasticity in conjunction with computations carried out on a high-speed calculating machine. Numerical results are obtained for several plate proportions and for one material. The results indicate plate strengths greater than those that have been found experimentally on plates that do not satisfy straight-edge conditions.—(33.2.4.5.1 × 33.2.2).

An analysis of the stability and ultimate compressive strength of short sheet-stringer panels with special reference to the influence of riveted connection between sheet and stringer. J. W. Semonian and J. P. Peterson. N.A.C.A., T.N. 3431 (*March* 1955).

A method of strength analysis of short sheet-stringer panels subjected to compression is presented which takes into account the effect that the riveted attachments between the plate and the stiffeners have on the strength of panels.—(33.2.4.6.1 × 33.2.4.6.6).